

## Prospects for a Low Carbon Energy Future

M.B. McElroy

Center for Earth & Planetary Physics, Harvard University, Pierce Hall, Cambridge, MA 02138; 617-495-2351,  
E-mail: mbm@seas.harvard.edu

The abundance of CO<sub>2</sub> is demonstrably higher now than at any time over the past 650,000 years and is likely over the next few decades to rise to levels not seen since dinosaurs roamed the Earth 50 million years ago. The increase in the abundance of CO<sub>2</sub> and a variety of other so-called greenhouse gases (notably CH<sub>4</sub> and N<sub>2</sub>O) has resulted in a serious perturbation to the global energy balance. The Earth is now radiating significantly less energy to space than it absorbs from the sun. The extra heat, stored largely in the ocean, is responsible for important changes in global and regional climate with consequences, which though difficult to predict in detail, are surely serious. This paper will discuss potential options for a low-carbon energy future. Options to be discussed include prospects for carbon capture and sequestration with particular attention to the potential for an energy future based largely on electricity produced from a combination of wind, solar and geothermal sources complemented to an extent by nuclear. Particular attention will be directed at the challenges faced by large developing countries such as China and India, the former now having surpassed the U.S. as the world's largest national source of greenhouse gas emissions.



Michael B. McElroy is the Gilbert Butler Professor of Environmental Studies in the Department of Earth & Planetary Sciences at Harvard University. He obtained a Ph. D. in Applied Mathematics, at Queen's University, Belfast, Northern Ireland. Previous positions include post doctoral work at the University of Wisconsin at Madison; Co-founder of Atmospheric and Environmental Research; Chairman, MEDEA, Task Force appointed by Vice-President Gore to advise on Environmental Aspects of U.S. Intelligence; and former Director of the Harvard University Center for the Environment. Michael has authored or co-authored over 200 publications on topics such as planetary atmospheres, oceanography, stratospheric ozone depletion, air quality, climate change, carbon dioxide budgets, renewable energy's implications on climate, environmental problems in developing countries and one book, *The Atmospheric Environment: Effects of Human Activity*, Princeton University Press (2002).

Michael received AGU's James B. Macelwane Award (1968), NASA Public Service Medal (1978) and the George Ledlie Prize from Harvard University.

## **An Update on Climate Services**

### C.J. Koblinsky

NOAA Climate Program Office, 1315 East West Hwy Room: 12837 Building: SSMC3, Silver Springs, MD 20910; 301-734-1200, E-mail: [chester.j.koblinsky@noaa.gov](mailto:chester.j.koblinsky@noaa.gov)

Dr. Chet Koblinsky is Director of NOAA's Climate Program Office. His responsibilities include a broad range of climate science and services programs, ranging from observations and data systems, research, model development, predictions, and impacts research to delivery of information. He manages NOAA's competitive climate research and observations programs.

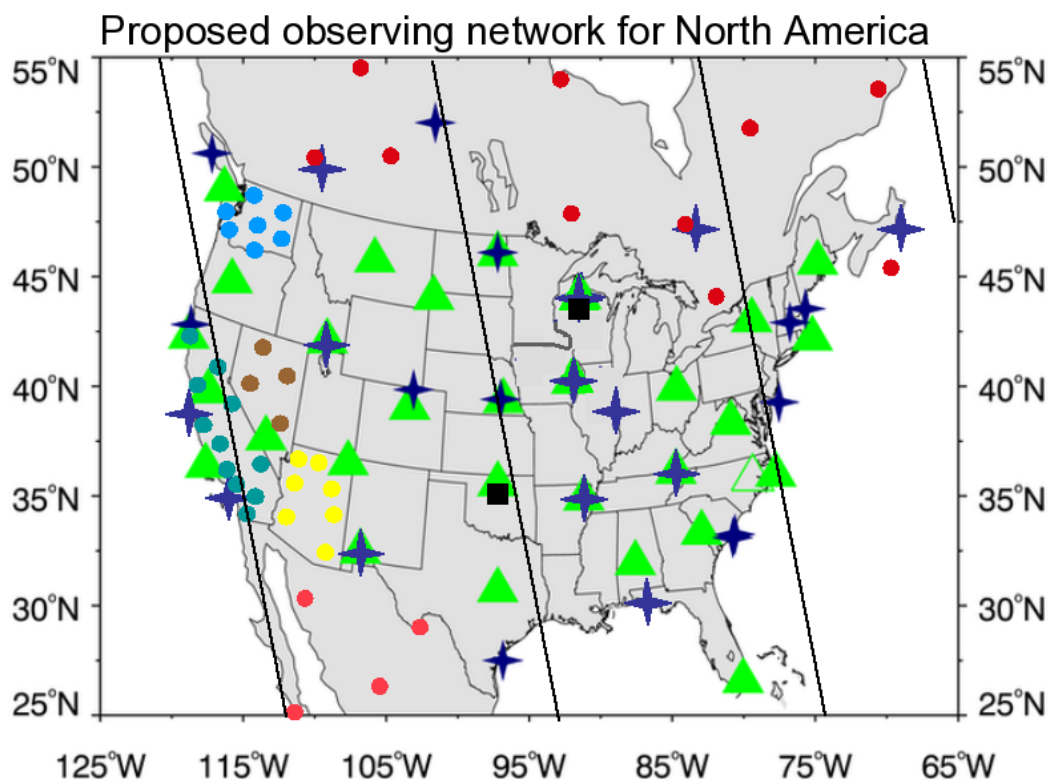


## Objective Verification of Greenhouse Gas Emissions and Removals

P.P. Tans

NOAA Earth System Research Laboratory, 325 Broadway, Boulder, CO 80305; 303-497-6678, E-mail: Pieter.Tans@noaa.gov

In the near future policies are expected to be enacted to greatly reduce emissions of greenhouse gases, especially of CO<sub>2</sub>. Their success should be observable at background sites such as Mauna Loa as a decreasing rate of the CO<sub>2</sub> build up, followed by a subsequent decline. It is very likely that the observed decline will be less, perhaps substantially, than hoped for. Which of these policies are not meeting their objectives? Because of some very long residence times, of CO<sub>2</sub> especially, we cannot afford failure. The challenge is to provide measurements that can quantify emissions on much smaller spatial scales, such as on the state and county level. Experience shows that we cannot rely solely on inventories that are often based on self-reporting. An outline will be given of a data assimilation approach, in which data from quite different sources are brought together in a coherent framework, in order to optimize the contribution from each data type and maximize the reliability of the overall results.



**Figure 1.** Conceptual design of network. Triangles: tall towers; stars: regular aircraft profiles; circles: regional and national networks; squares: upward looking spectrometers; lines: daily satellite orbits.

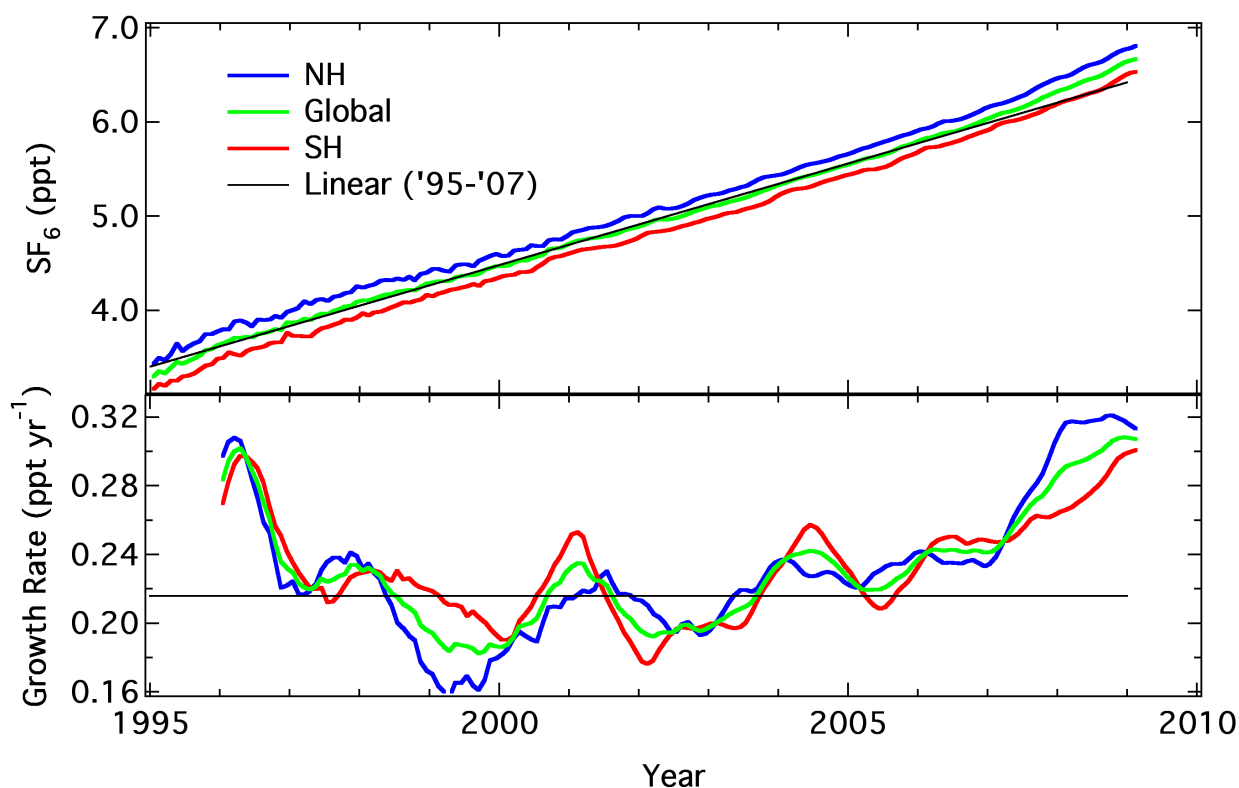
## Atmospheric Emissions of Sulfur Hexafluoride: A Challenge for the Future

J.W. Elkins<sup>1</sup>, G.S. Dutton<sup>2</sup>, B.D. Hall<sup>1</sup>, D.F. Hurst<sup>2</sup>, F.L. Moore<sup>2</sup>, D.J. Mondeel<sup>2</sup>, J.D. Nance<sup>2</sup> and E.J. Dlugokencky<sup>1</sup>

<sup>1</sup>NOAA Earth System Research Laboratory, 325 Broadway, Boulder, CO 80305; 303-497-6224, E-mail: james.w.elkins@noaa.gov

<sup>2</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309

Atmospheric sulfur hexafluoride ( $\text{SF}_6$ ) has become one of the fastest growing minor greenhouse gases since the development of the NOAA ESRL Annual Greenhouse Gas Index (AGGI, base year = 1990). Its total radiative forcing could become a major concern in the near future. On a per molecule basis, it is almost 22,200 times more effective as an infrared absorber than carbon dioxide ( $\text{CO}_2$ ), but its global mixing ratio is much less where global mean mixing ratios are almost 6.5 parts-per-trillion (ppt) compared to 385 parts-per-million for  $\text{CO}_2$ . It is used almost exclusively as an electric insulating gas for the distribution of electric power. It also has a long atmospheric lifetime, estimated between 500 and 3200 years. Over the past two years, the atmospheric growth rate has accelerated from an average of 0.21 ppt year to 0.31 ppt year. The major problem with dielectric gases used in power distribution is that there is no known environmentally friendly substitute for  $\text{SF}_6$ . Mankind's demand for electricity over the long term will grow with population. A switch from less fossil fuel technology to more alternative energy sources like wind, solar, tidal action, and biofuels will still require  $\text{SF}_6$ . This talk will highlight recent observations from NOAA ESRL's flask and *in situ* ground base networks, along with recent airborne regional and global campaigns.



**Figure 1.** Global and Hemispheric Means of  $\text{SF}_6$  (top panel), Respective growth rate, noting clear departure from linear growth in 2007 (bottom panel).



## NOAA's Science On a Sphere - The Ideal Way to Display Global Data

B. Russell

NOAA Earth System Research Laboratory, 325 Broadway, Boulder, CO 80305; 303-497-6759, E-mail: [beth.russell@noaa.gov](mailto:beth.russell@noaa.gov)

Science On a Sphere® (SOS) is a room-sized, global display system that uses computers and video projectors to display planetary data on a six foot globe. Invented by Dr. Alexander MacDonald, Director of the NOAA Earth System Research Laboratory (ESRL), SOS is installed in over 35 locations around the world, including science museums, universities, planetariums and aquariums. Over 250 datasets can be shown on the sphere ranging from climate models to movement of tectonic plates to sea surface height anomalies. Many NOAA datasets, including datasets from ESRL Global Monitoring Division (GMD), are shown at the SOS sites around the world. This provides valuable exposure for NOAA's research. CarbonTracker, from GMD, has been shown in many museums and was recently highlighted on SOS at an exhibit for the National Science Teachers Association annual conference. Continued growth of the SOS dataset library is supported by researchers making their global data available for SOS. Once generated, new data is then made available to all SOS sites with a brief description of the data so that it can be shown and taught in all the SOS venues. SOS promotes environmental literacy by displaying NOAA's Earth science data in a way that engages and educates audiences of all ages. In a survey at the McWane Science Center in Birmingham, AL, 100% agreed that the Science on a Sphere® images made a complex topic more understandable and 82% agreed that they learned something new from the exhibit.



**Figure 1.** School groups regularly visit the Earth System Research Laboratory (ESRL) to see Science On a Sphere (SOS) in the Planet Theater. Tom LeFebvre, of ESRL's Global Systems Division, is seen here giving a presentation of SOS to a class of captivated 5th graders. NOAA photo by Will von Dauster.

## PFC Emissions from Global and Australian Aluminium Production Using AGAGE Data

P. Fraser<sup>1</sup>, J. Muhle<sup>2</sup>, C. Trudinger<sup>1</sup>, A. Ganesan<sup>2</sup>, B. Dunse<sup>1</sup>, B. Miller<sup>3,2</sup>, C. Harth<sup>2</sup>, P. Krummel<sup>1</sup>, P. Salameh<sup>2</sup>, R. Weiss<sup>2</sup>, P. Steele<sup>1</sup> and R. Prinn<sup>4</sup>

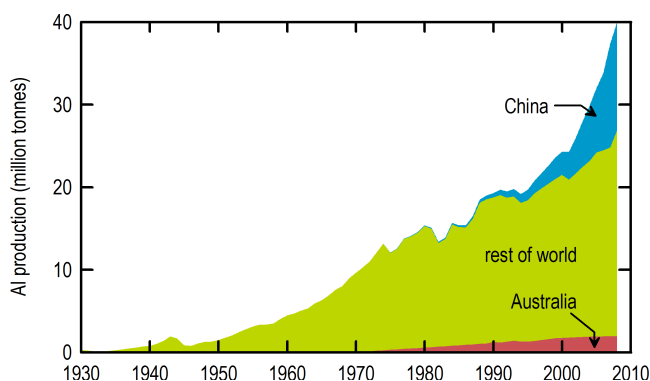
<sup>1</sup>Light Metals Flagship, Commonwealth Scientific & Industrial Research Organization, Marine and Atmospheric Research, Aspendale, Victoria 3195, Australia; +61393994613, E-mail: paul.fraser@csiro.au

<sup>2</sup>Scripps Institution of Oceanography, University of California at San Diego, La Jolla, CA 92037

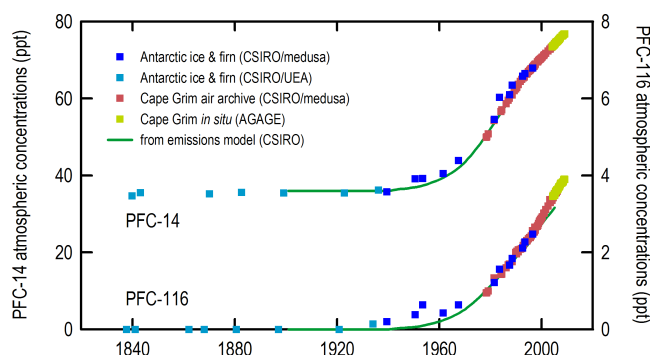
<sup>3</sup>NOAA Earth System Research Laboratory, Boulder, CO 80305

<sup>4</sup>Department of Earth, Atmospheric and Planetary Science, Massachusetts Institute of Technology, Cambridge, MA 02139

Perfluorocarbons (PFC-14:  $\text{CF}_4$ , PFC-116:  $\text{C}_2\text{F}_6$ ) are powerful greenhouse gases released during the production of aluminium and from the electronic industry. PFCs remain in the atmosphere for 1000s of years and are targeted for controls in global and Australian strategies to reduce greenhouse gas emissions. In Australia, PFCs account for about 20% of the greenhouse gases released at the smelter during the production of aluminium, the remaining 80% being carbon dioxide from the production (15%) and consumption (65%) of carbon anodes during the electrolysis of alumina ( $2\text{Al}_2\text{O}_3 + 3\text{C} \rightarrow 6\text{Al} + 3\text{CO}_2$ ) (Keniry, 2007). Global production of primary aluminium is growing at 8% per year, driven by the huge demand in China (Figure 1), currently growing at about 20-35% per year. Australian aluminium production (6% of global) is growing at 2% per year (IAI, 2008). AGAGE global atmospheric observations of PFCs can be used to calculate time-dependent global PFC emissions, which, when coupled with information on global aluminium production and the emission of PFCs from the electronics industry, lead to time-dependent, globally-averaged PFC emission factors for aluminium production (Mühle et al., 2008). Atmospheric PFC observations made at Cape Grim, Tasmania (*in situ*, air archive, 1978-2008), and at Aspendale, Victoria (2006-2008) and on Antarctic air tapped in ice and firn (1840-2000), using a Medusa GC-MS system (Miller et al., 2008), are used to deduce time-dependent Australian PFC emissions and emission factors (Fraser et al., 2007). The global and Australian aluminium industries have set a target of reducing PFC emission factors (PFC released per tonne of aluminium produced) by 80% from 1990 levels by 2010.



**Figure 1.** Global aluminium production (IAI, 2008).



**Figure 2.** PFCs in the Southern Hemisphere from AGAGE measurements at Cape Grim, on the Cape Grim air archive and on air samples from Antarctic firn and ice (Fraser et al., 2007).  $\text{CF}_4$  data are in the SIO 2005 scale,  $\text{C}_2\text{F}_6$  data in the preliminary SIO 2007 scale.

## Towards an Understanding of Inter-Annual Variations in Tropospheric OH Since 1998 from Observations of Reduced Trace Gases

S. Montzka<sup>1</sup>, E. Dlugokencky<sup>1</sup>, M. Krol<sup>2</sup>, J. Lelieveld<sup>3</sup> and P. Jockel<sup>3</sup>

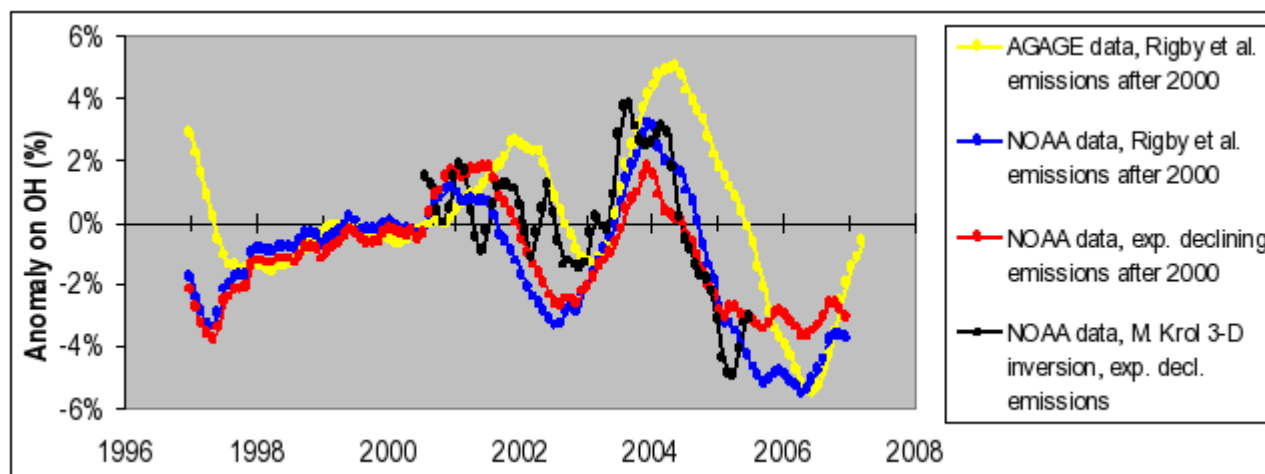
<sup>1</sup>NOAA Earth System Research Laboratory, 325 Broadway, Boulder, CO 80305; 303-497-6657, E-mail: steve.montzka@noaa.gov

<sup>2</sup>Institute for Marine and Atmospheric Research, Utrecht University, Utrecht, Netherlands

<sup>3</sup>Max Planck Institute for Chemistry, Mainz, Germany

Can the oxidizing capacity of the atmosphere, as controlled by the hydroxyl radical (OH), change by 10 to 20% from year to year? Or is the global OH abundance buffered against large interannual variations in emissions by biomass burning, industrial pollution, solar radiation, water vapor, and other OH sources and sinks? Past work suggests a wide range of potential sensitivities and, therefore, accurate projections of future atmospheric changes are problematic. Studies of methyl chloroform observations made in the 1980s and 1990s suggest OH could be highly sensitive to interannual variations in the atmospheric environment. Such variations are difficult to reconcile with the rather low variability observed for atmospheric methane. Furthermore, model studies suggest a much lower sensitivity for OH to such changes in precursors and sinks because of balancing effects by chemical and transport processes.

We have argued recently that methyl chloroform ( $\text{CH}_3\text{CCl}_3$ ) observations since 1998 should provide a more precise estimate of OH interannual variability because errors associated with large atmospheric gradients and emissions have become small. Our analysis shows, for example, that OH variations inferred from  $\text{CH}_3\text{CCl}_3$  since 1998 are much smaller than during earlier decades. But has the precision of the analysis improved to the point that OH variability over the past decade can be accurately discerned? Do results from different trace gases provide a consistent picture regarding the magnitude and phase of OH variations? What do model calculations suggest? How consistent are inferences regarding OH variability when one considers results for  $\text{CH}_3\text{CCl}_3$  from different laboratories, different emissions histories, or model analyses of varying sophistication, especially given that atmospheric mixing ratios of  $\text{CH}_3\text{CCl}_3$  are now quite small (10 ppt)? This presentation will focus on addressing these questions and improving our understanding of the stability of the atmosphere's oxidation capacity.



**Figure 1.** Estimates of anomalies on OH derived from independent global surface measurements of  $\text{CH}_3\text{CCl}_3$  (yellow line: AGAGE from Prinn et al., 2005; and blue line: NOAA); two different emission histories for  $\text{CH}_3\text{CCl}_3$  since 2000: exponentially declining at 20%/yr or from Rigby et al. (2008) (yellow and blue lines); and two different modeling approaches: a simple 1-box analysis (Montzka et al., 2000) and a 3-D inversion with inter-annually varying meteorology (Krol et al. 2003) (black line).

## Regional Estimates of CH<sub>4</sub> and N<sub>2</sub>O Emissions from Central California

M.L. Fisher<sup>1</sup>, C. Zhao<sup>1</sup>, A.E. Andrews<sup>2</sup>, L. Bianco<sup>2</sup>, E. Dlugokencky<sup>2</sup>, J. Kofler<sup>3</sup>, J. Eluszkiewicz<sup>4</sup>, C. MacDonald<sup>5</sup> and T. Nehrkorn<sup>4</sup>

<sup>1</sup>Lawrence Berkeley National Laboratory, MS 90K-125 1 Cyclotron Rd., Berkeley, CA 94720; 510-486-5539, E-mail: mlfischer@lbl.gov

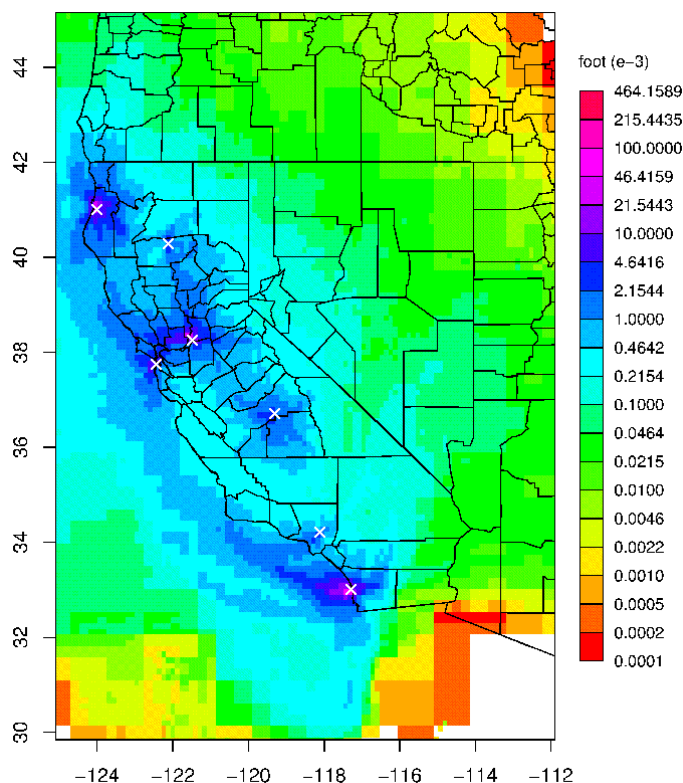
<sup>2</sup>NOAA Earth System Research Laboratory, Boulder, CO 80305

<sup>3</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309

<sup>4</sup>Atmospheric and Environmental Research, Inc., Lexington, MA 02421

<sup>5</sup>Sonoma Technology, Inc., Petaluma, CA 94954

Methane and nitrous oxide mixing ratios measured at a tall-tower are compared to model predictions to estimate surface emissions of CH<sub>4</sub> and N<sub>2</sub>O from Central California for the October, 2007 to September, 2008. Predicted mixing ratios are calculated based on spatially resolved a priori CH<sub>4</sub> and N<sub>2</sub>O emissions and simulated atmospheric trajectories. The atmospheric trajectories, along with surface footprints, are computed using the Weather Research and Forecast (WRF) coupled to the Stochastic Time-Inverted Lagrangian Transport (STILT) model. An uncertainty analysis is performed to provide quantitative uncertainties in estimated emissions. Linear regressions of modeled and measured mixing ratios obtain slopes near unity for CH<sub>4</sub> but some what less than unity for N<sub>2</sub>O, suggesting that actual CH<sub>4</sub> emissions were within 25% of the inventory estimates but N<sub>2</sub>O emissions were underestimated. A Bayesian source sector analysis obtains CH<sub>4</sub> posterior scaling factors for different sources, suggesting that several of the sources (e.g., landfills, natural gas use, petroleum production, crops, and wetlands) are roughly consistent with inventory estimates but livestock emissions are ~80% higher than the inventory estimates. A Bayesian “region” analysis is also carried out for CH<sub>4</sub> and N<sub>2</sub>O emissions using 13 sub-regions within California. Only regions near the tower are significantly constrained by the tower measurements, but CH<sub>4</sub> emissions from the south Central Valley appear to be underestimated in a manner consistent with the under-prediction of livestock emissions. A pseudo-experiment using predicted CH<sub>4</sub> signals is also performed to explore the uncertainty reductions that might be obtained if additional tower measurements were made in a network of tall-tower stations in California, showing that it should be possible to provide high-accuracy retrievals of surface CH<sub>4</sub> emissions for multiple regions.



**Figure 1.** The monthly mean footprint maps for seven tower stations (each marked with an x) simulated for Oct, 2007.



## Tetrafluoromethane in the Global Atmosphere

J. Mühle<sup>1</sup>, B.R. Miller<sup>1,6</sup>, P.K. Salameh<sup>1</sup>, C.M. Harth<sup>1</sup>, B.R. Gready<sup>2</sup>, S. O'Doherty<sup>2</sup>, A. Ganesan<sup>3</sup>, C.M. Trudinger<sup>4</sup>, L.W. Porter<sup>5</sup>, L.P. Steele<sup>4</sup>, P.B. Krummel<sup>4</sup>, V.V. Petrenko<sup>1,7</sup>, M. Rigby<sup>3</sup>, P.G. Simmonds<sup>2</sup>, P.J. Fraser<sup>4</sup>, R.G. Prinn<sup>3</sup> and R.F. Weiss<sup>1</sup>

<sup>1</sup>Scripps Institution of Oceanography, 9500 Gilman Dr. 0244, La Jolla, CA 92093; 858-534-2599, E-mail: jens@gaslab.ucsd.edu

<sup>2</sup>School of Chemistry, University of Bristol, Bristol BS8 1TS, United Kingdom

<sup>3</sup>Department of Earth, Atmospheric and Planetary Science, Massachusetts Institute of Technology, Cambridge, MA 02139

<sup>4</sup>Commonwealth Scientific & Industrial Research Organization, Marine and Atmospheric Research, Aspendale, VIC 3195, Australia

<sup>5</sup>Centre for Australian Weather and Climate Research, Bureau of Meteorology, Melbourne, Victoria 3001, Australia

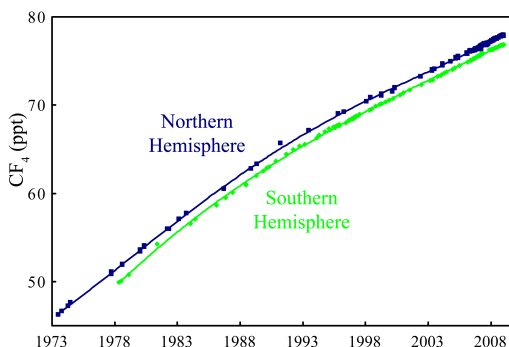
<sup>6</sup>NOAA Earth System Research Laboratory, Boulder, CO 80303

<sup>7</sup>Institute for Arctic and Alpine Research, University of Colorado, Boulder, CO 80309

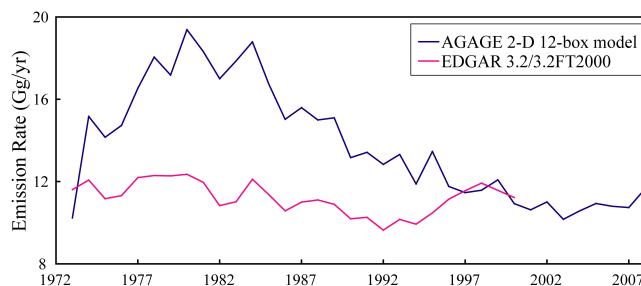
Tetrafluoromethane (CF<sub>4</sub>) has been measured with high precision (<0.3%) and accuracy (~1%) *in situ* and in archived air samples from both hemispheres using the Medusa GC/MS developed for the Advanced Global Atmospheric Gases Experiment (AGAGE) program. CF<sub>4</sub> has increased from ~50 to ~77 ppt from 1978 to 2008 in the Southern Hemisphere and from ~46 to ~78 ppt from 1973 to 2008 in the Northern Hemisphere (Figure 1). Based on the SIO-2005 calibration scale, developed at the Scripps Institution of Oceanography, the abundance of this potent and long-lived greenhouse gas is ~7% lower than previously reported, but CF<sub>4</sub> is still by far the most abundant perfluorinated trace gas. Pre-industrial abundances of CF<sub>4</sub> were determined in air extracted from Greenland ice (12–19 kyr BP) and Antarctic firn.

It is known that CF<sub>4</sub> is released mainly from primary aluminum production and from semiconductor and flat panel display production. Its large pre-industrial abundance has been explained by emissions from fluorites and granites in the continental lithosphere. With the AGAGE 2-D 12-box model we determined that global anthropogenic CF<sub>4</sub> emissions peaked at ~19 Gg/yr in the early to mid-1980s (Figure 2) – along with strong increases in primary aluminum production. Emissions declined to ~12 Gg/yr in the mid-1990s, probably due to reduced emissions from the aluminum industry, and have been flat at ~11 Gg/yr since ~1990, reflecting a balance of improved technology versus increased production in the aluminum industry, and emissions from the electronics industry. Global emissions prior to ~1995 are clearly underestimated in the EDGAR inventory.

It is difficult to quantify the contributions of these different sources, particularly due to ill-defined emission factors and substantially increasing but poorly known aluminum production in Asia. High-frequency *in situ* CF<sub>4</sub> data from the new AGAGE-affiliated station in Korea (Gosan, Jeju Island, Seoul National University) will enable us to better quantify regional Asian emissions, and thus help to resolve the contributions to the global CF<sub>4</sub> flux from these important sources.



**Figure 1.** CF<sub>4</sub> (ppt) in the Northern and Southern Hemisphere from archive and *in-situ* measurements.



**Figure 2.** Global CF<sub>4</sub> emissions (Gg/yr).

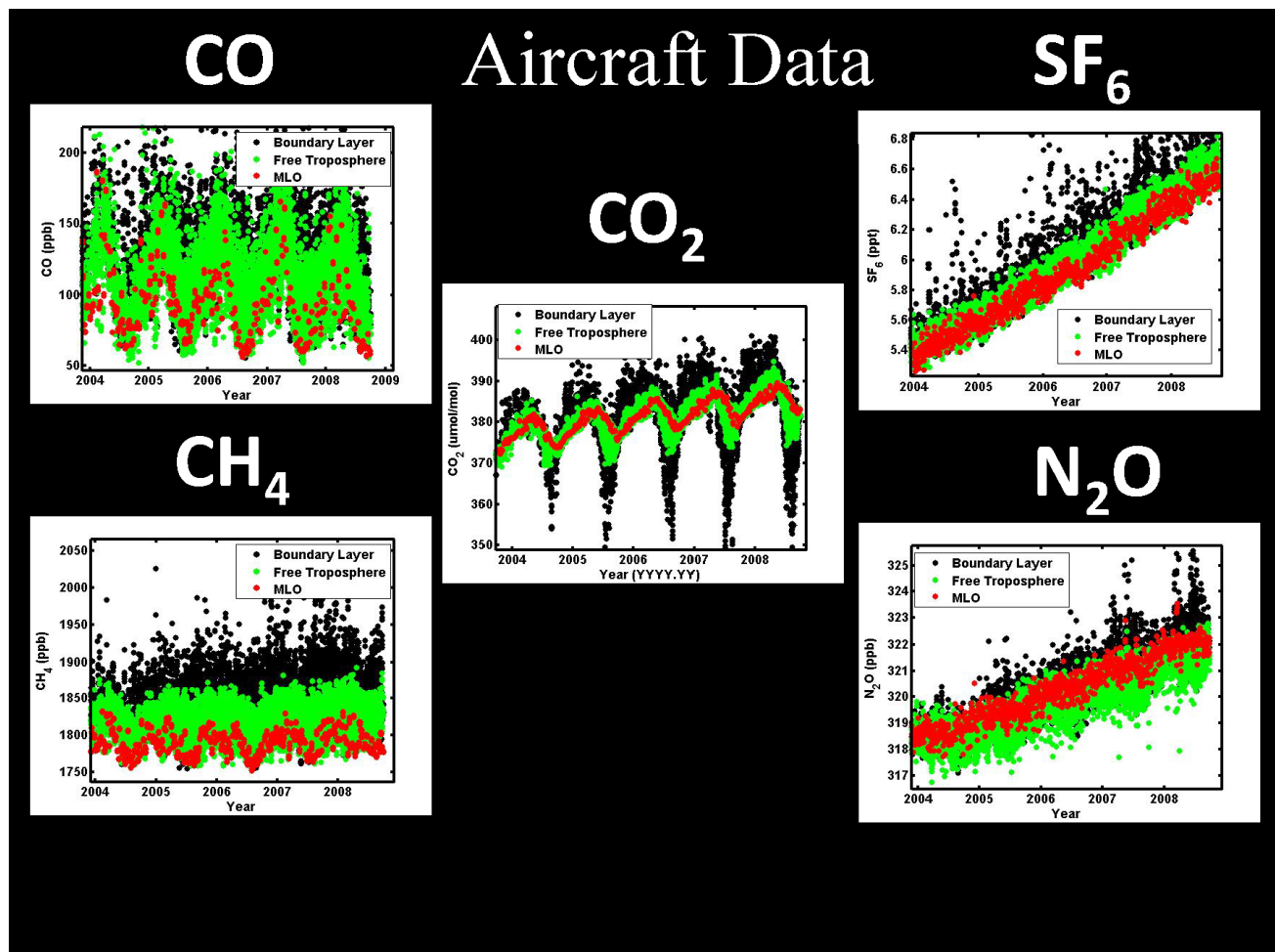
## Observations of Non-CO<sub>2</sub> Greenhouse Gases Over North America from the NOAA ESRL Carbon Cycle Group Aircraft Project

C. Sweeney<sup>1</sup>, A. Karion<sup>1</sup>, L. Bruhwiler<sup>2</sup>, T. Conway<sup>2</sup>, E. Dlugokencky<sup>2</sup>, D. Guenther<sup>1</sup>, K. Masarie<sup>2</sup>, B. Miller<sup>1</sup>, S.A. Montzka<sup>2</sup>, P. Lang<sup>2</sup>, D. Neff<sup>1</sup>, P. Novelli<sup>2</sup>, P. Tans<sup>2</sup> and S. Wolter<sup>1</sup>

<sup>1</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309; 303-497-4771, E-mail: colm.sweeney@noaa.gov

<sup>2</sup>NOAA Earth System Research Laboratory, Boulder, CO 80305

The NOAA ESRL Carbon Cycle Group Aircraft Project has been making measurements of CO<sub>2</sub>, CH<sub>4</sub>, CO, N<sub>2</sub>O and SF<sub>6</sub> for more than 4 years at 16 sites around North America. A compilation of vertical profiles from 500 m above ground level to 8000 m of these gases relative to trends observed at Mauna Loa Observatory gives a unique look at potential sources and sinks of each gas as well as the large scale circulation that drives longitudinal and latitudinal gradients observed for each gas. In this study we will focus on the vertical and horizontal distribution of CH<sub>4</sub>, CO, N<sub>2</sub>O and SF<sub>6</sub> over North America to understand the transport of non-CO<sub>2</sub> greenhouse gases out of mid-latitude boundary layer to high latitude regions.



**Figure 1.** CO<sub>2</sub>, CH<sub>4</sub>, CO, N<sub>2</sub>O and SF<sub>6</sub> measurements made over North America by the NOAA ESRL Carbon Cycle Group Aircraft Project in the last 10 years. Red shows measurements made at Mauna Loa Observatory (MLO), green dots shows free troposphere measurements and black dots show measurements below 1500 magl.

## **In Memory of Derek Cunnold**

10 July 1940 – 18 April 2009

Derek Cunnold died suddenly and unexpectedly in Dunwoody, Georgia on Saturday, 18 April 2009. He was an internationally recognized and respected expert regarding the science of Earth's protective ozone layer, the use of satellite measurements and computer models to study this complex layer, and the interpretation of global atmospheric measurements to determine the sources and sinks of ozone-depleting and greenhouse gases. He also collaborated extensively with many scientists at NOAA, and whose loss will be felt deeply by them on a personal and professional level. He co-founded the international Advanced Global Atmospheric Gases Experiment (AGAGE) that has observed trace gases continuously over the globe for the past 31 years. He received the NASA Medal for Outstanding Achievement in 1992, was a Lead Author for the United Nations Environment Programme/World Meteorological Organization (UNEP/WMO) 2006 Scientific Assessment of Ozone Depletion, and was a member of nine NASA international satellite experiment teams. He joined the faculty at Georgia Tech in 1979, became a Full Professor in 1997, and was Chair of the School of Earth and Atmospheric Sciences from 1997 to 1999, and was conferred Professor Emeritus in 2006. He was an outstanding mentor for students and young scientists at both Georgia Tech and other institutions, including NOAA. Many have described him as “a gentleman and a scholar.” He is survived by his wife Susan, daughters Carolyn and Alison and son David, their spouses, three grandchildren, a brother and a sister, and their spouses.

His long-term collaborator, Professor Ron Prinn at MIT, comments that “Derek's intelligence, insight, scientific achievements, unselfish service, and quiet, wise, and effective leadership will be deeply missed, but never forgotten, by me and his many scientific colleagues and admirers around the world.”

Oral tributes will be presented.



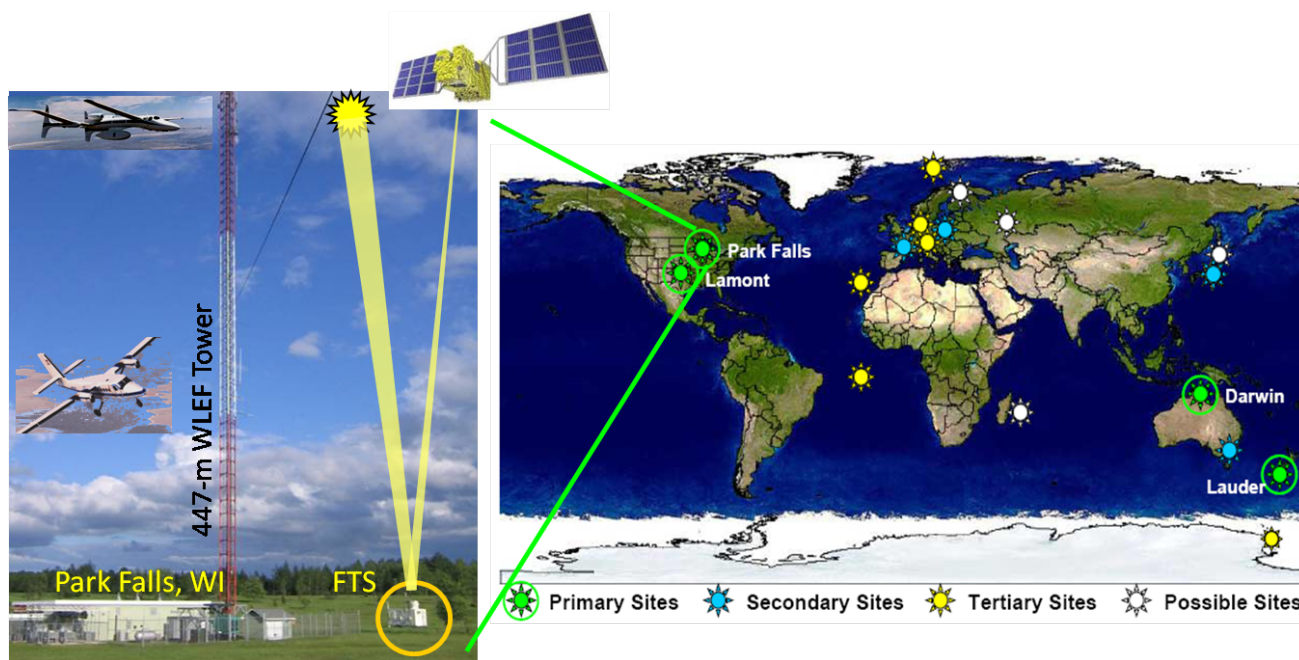


## Space-Based Measurements for Long-Term Global Monitoring of Atmospheric CO<sub>2</sub>

D. Crisp

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109; 818-687-9939, E-mail: David.Crisp@jpl.nasa.gov

Measurements of reflected sunlight in near infrared CO<sub>2</sub> and O<sub>2</sub> absorption bands with instruments such as the recently launched Japanese IBUKI TANSO-Fourier Transform Spectrometer (FTS) provide new opportunities for long-term, global, space-based monitoring of CO<sub>2</sub> and other greenhouse gases. These measurements must be thoroughly validated to demonstrate their accuracy and range of validity. Prior to the failure of the NASA Orbiting Carbon Observatory (OCO) launch, the OCO team developed a comprehensive validation strategy, designed to relate these space based measurements to the World Meteorological Organization (WMO) CO<sub>2</sub> standard that is maintained by NOAA ESRL Global Monitoring Division. A critical element of this strategy was the Total Carbon Column Observing Network (TCCON), which uses high resolution FTS's to measure the absorption of direct sunlight by CO<sub>2</sub> and O<sub>2</sub>, in the same spectral regions used by the TANSO-FTS (Figure 1). Over-flights of TCCON stations by aircraft carrying *in situ* instruments calibrated with WMO referenced gases have been used to validate the TCCON results. CO<sub>2</sub> profiles extending from the boundary layer to the middle troposphere are integrated to derive a value of XCO<sub>2</sub>. Simultaneous TCCON FTS and TANSO-FTS measurements are then compared to transfer the WMO standard to the spacecraft measurements. To further validate these space-based measurements, they can be assimilated into global carbon source/sink inversion models to derive near-surface CO<sub>2</sub> fields that can be validated against measurements from the Cooperative Air Sampling Network. We now plan to use these methods to assist in the validation of IBUKI results.



**Figure 1.** (Left) TCCON station at Park Falls, WI shown adjacent to the WLEF Tower. (Right) Map of TCCON stations.

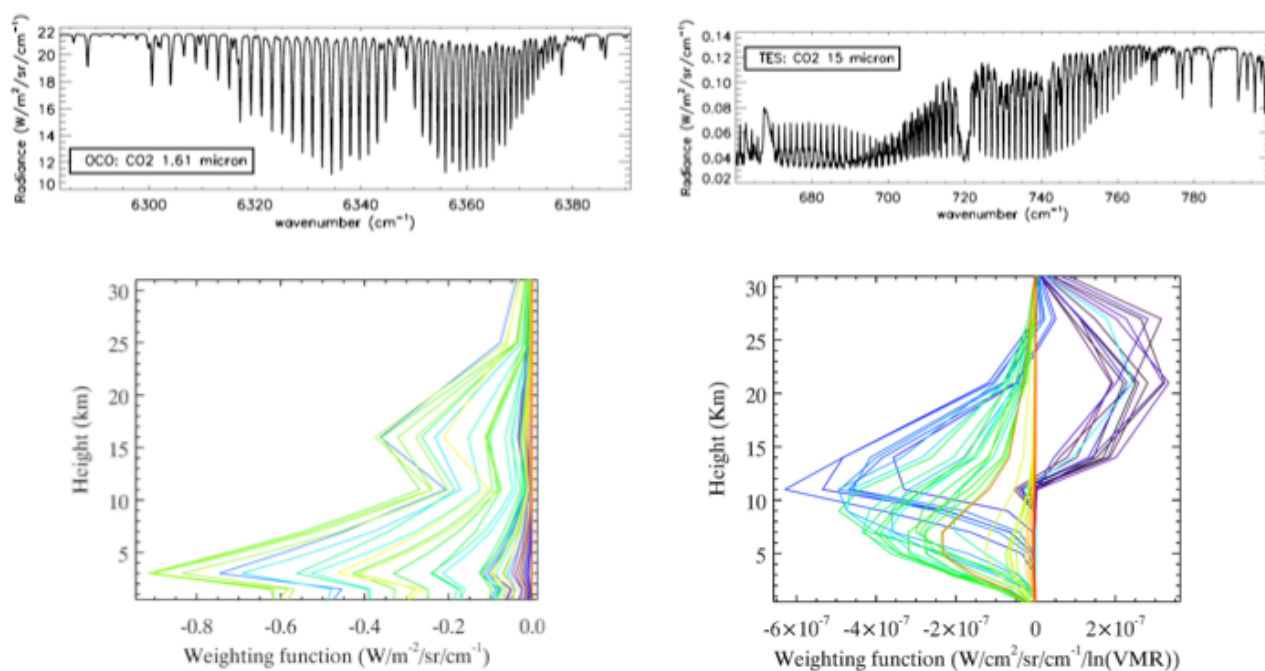
## CO<sub>2</sub> Vertical Profiles from Simultaneous Retrievals of Near Infrared and Thermal Infrared Satellite Data

C. Miller<sup>1</sup>, S. Kulawik<sup>1</sup>, K. Bowman<sup>1</sup>, L. Kuai<sup>2</sup>, V. Natraj<sup>2</sup>, R. Shia<sup>2</sup> and Y. Yung<sup>2</sup>

<sup>1</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, ; 818-393-6294, E-mail: charles.e.miller@jpl.nasa.gov

<sup>2</sup>California Institute of Technology, Pasadena, CA 91125

We are developing atmospheric CO<sub>2</sub> vertical profile data products from simultaneous retrievals of near infrared and thermal infrared satellite observations (Figure 1). These data will significantly improve the estimation of atmospheric carbon sources and sinks by providing powerful observational constraints on vertical as well as horizontal and temporal distributions of atmospheric CO<sub>2</sub> in data assimilation and data fusion approaches. Accurate vertical transport is essential within the source/sink inversion to avoid systematic flux errors of up to 2 GtC/yr since convection over land is strongly correlated in time with photosynthesis, the dominant surface sink for CO<sub>2</sub>.



**Figure 1.** Spectra (top) and averaging kernels (bottom) for simulated space-based near infrared and infrared atmospheric CO<sub>2</sub> observations. Simulations are based on NASA's Orbiting Carbon Observatory (OCO, left) and Thermal Emission Spectrometer (TES, right) instruments. The complementarity of the vertical components in the two averaging kernels provides multiple degrees of freedom for signal in the CO<sub>2</sub> vertical profile solution. Similar results are possible using (nearly) simultaneous thermal emission observations from the Atmospheric Infrared Sounder (AIRS), or from collocated near infrared and thermal infrared observations of JAXA's GOSAT (IBUKI) sensors.

# Global Distribution of CO<sub>2</sub> in Mid Troposphere from the Atmospheric Infrared Sounder (AIRS) Measurements Suggests Greater Cross Equator Exchange

Y.L. Yung<sup>1</sup>, R.L. Shia<sup>1</sup>, X. Jiang<sup>2</sup>, M.C. Liang<sup>3</sup>, K.F. Li<sup>4</sup>, L. Kuai<sup>4</sup>, M. Chahine<sup>5</sup>, E.T. Olsen<sup>5</sup> and L. Chen<sup>5</sup>

<sup>1</sup>Division of Geological and Planetary Sciences, California Institute of Technology, 150-21 Caltech, Pasadena, CA 91125; 626-395-6940, E-mail: yly@gps.caltech.edu

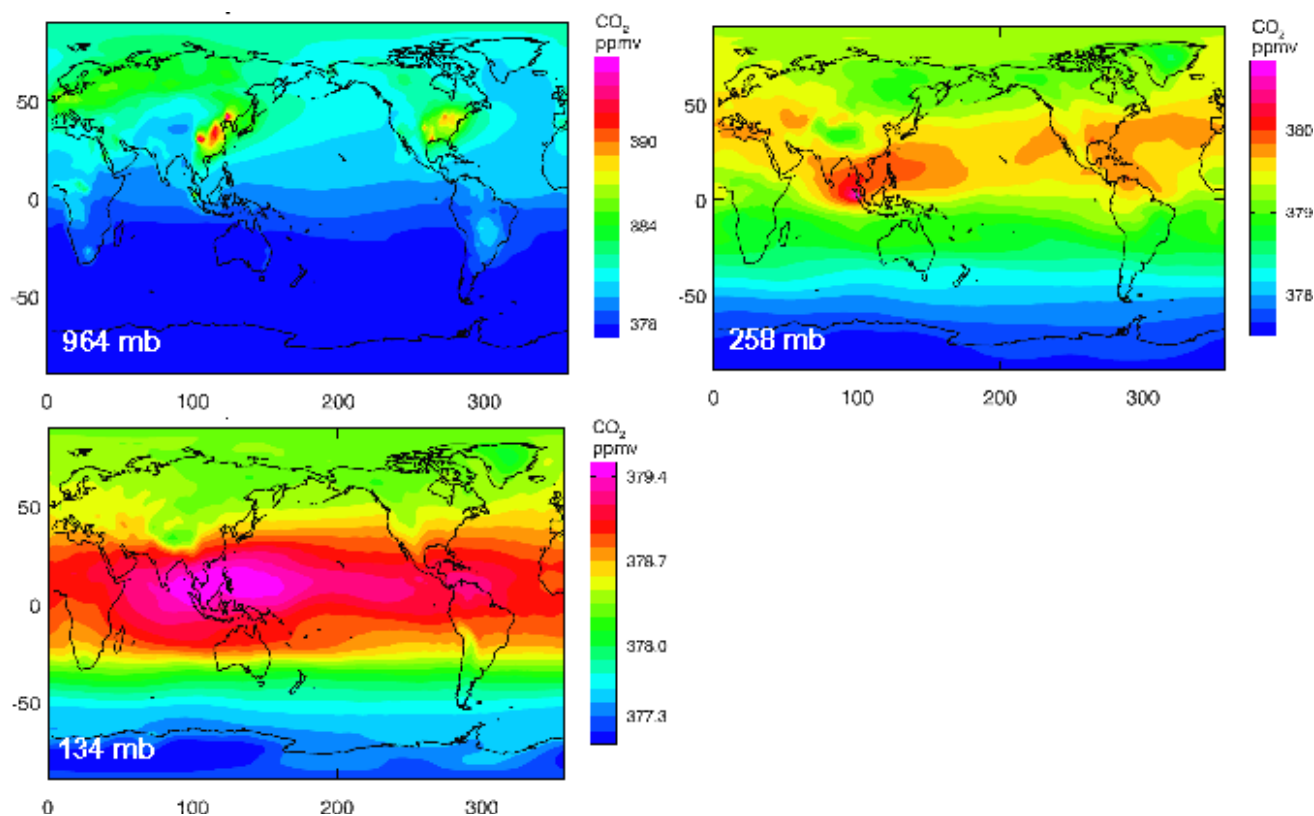
<sup>2</sup>Department of Earth and Atmospheric Sciences, University of Houston, Houston, TX 77204

<sup>3</sup>Research Center for Environmental Changes, Academia Sinica, Nankang, Taipei 115, Taiwan

<sup>4</sup>Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125

<sup>5</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

The Atmospheric Infrared Sounder (AIRS) enables us to monitor the global distribution and transport of middle tropospheric CO<sub>2</sub> over oceans, land and the poles (Chahine et al., 2008). Mid tropospheric CO<sub>2</sub> retrieved by AIRS shows a substantial spatiotemporal variability that is supported by aircraft flash sampling measurements (Matsueda et al., 2002; Machida et al. 2008). These data can be used to constrain the cross equator exchange of CO<sub>2</sub>. The uncertainties in the cross equator exchange of CO<sub>2</sub> affect the reliability of the estimations of the CO<sub>2</sub> sources and sinks in both hemispheres (Tans et al., 1990 and Fan et al., 1998). We use the Caltech/JPL 2-D chemistry and transport model (Shia et al., 2006) to simulate the mid troposphere CO<sub>2</sub>. The model is used to calculate the cross equator transport of CO<sub>2</sub>. Preliminary results indicate more inter-hemispheric transport than that implied by the ground-based data. Implications for CO<sub>2</sub> abundance and distribution in the southern hemisphere are discussed.



**Figure 1.** CO<sub>2</sub> distribution simulated from MOZART. Three levels (964mb, 258mb and 134mb) are shown.

## Validation of Six Years of Mid-Tropospheric CO<sub>2</sub> Data from the Atmospheric Infrared Sounder AIRS

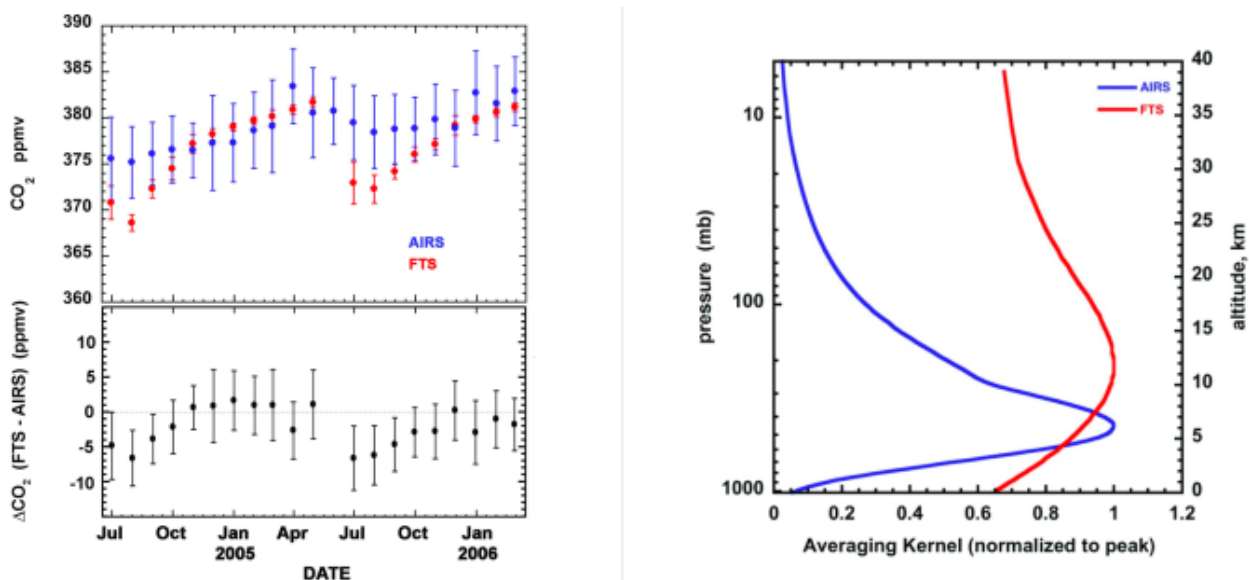
E. Olsen<sup>1</sup>, M.T. Chahine<sup>1</sup>, L.L. Chen<sup>1</sup>, X. Jiang<sup>2</sup>, T.S. Pagano<sup>1</sup> and Y.L. Yung<sup>3</sup>

<sup>1</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109; 818-354-4443, E-mail: edward.t.olsen@jpl.nasa.gov

<sup>2</sup>University of Houston, Houston, TX 77204

<sup>3</sup>California Institute of Technology, Pasadena, CA 91125

The retrieved distributions of mid-tropospheric CO<sub>2</sub> from the Atmospheric Infrared Sounder using the Vanishing Partial Derivative algorithm are compared to *in situ* measurements by commercial and research aircraft and to retrievals by land-based upward-looking Fourier Transform Interferometers. Estimates of AIRS CO<sub>2</sub> accuracy depend on the type and proximity of the measurements to the satellite footprint but remain between 1-2 ppm, under clear and cloudy conditions and over both land and oceans, between latitudes 30°S and 80°N. The seasonal phases are captured and the latitude variability in amplitude is validated. Also, the rate of growth of CO<sub>2</sub> over the six-year period is computed between 60°N-60°S latitudes as 2.02±0.08 ppm/year.



**Figure 1.** Seasonal variation of monthly average AIRS retrieved CO<sub>2</sub> within 250 km of Park Falls, Wisconsin compared to monthly average Park Falls Fourier Transform Spectrometer measured total column CO<sub>2</sub> and their differences.

# High Resolution CO<sub>2</sub> Transport Modeling System WRF-VRPM and Its Application in Interpretation of CO<sub>2</sub> Measurements

R. Ahmadov<sup>1</sup>, C. Gerbig<sup>1</sup>, R. Kretschmer<sup>1</sup>, D. Pillai<sup>1</sup>, C. Rödenbeck<sup>1</sup>, T. Koch<sup>1</sup> and G. Pétron<sup>2</sup>

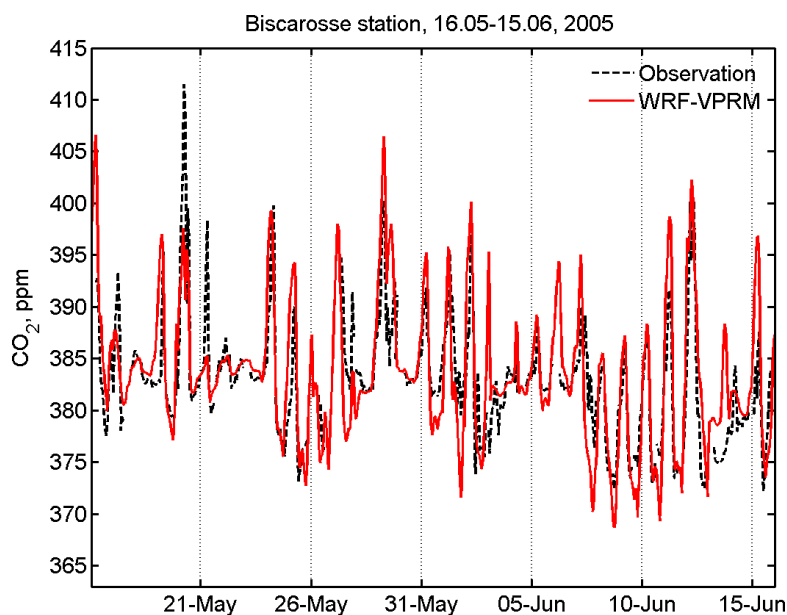
<sup>1</sup>Max-Planck-Institute for Biogeochemistry, P.O.Box 100164, Jena 07701, Germany; +49-3641-576361, E-mail: rahmadov@bgc-jena.mpg.de

<sup>2</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309

The global scale coarse resolution atmospheric models that are used in the inversions of CO<sub>2</sub> have difficulties to properly resolve complex mesoscale circulations around continental measurement sites. Moreover vertical mixing and boundary layer dynamics over the continent remain a big challenge for all transport models. In order to better understand the impact of mesoscale transport effects and vertical mixing on atmospheric CO<sub>2</sub> distributions, we have used the Weather Research and Forecasting (WRF) model coupled to the diagnostic biosphere model Vegetation Photosynthesis and Respiration Model (VPRM), which provides high-resolution biospheric CO<sub>2</sub> fluxes based on MODIS satellite vegetation indices. We have run WRF-VPRM for different seasons in 2005 and 2007, covering the intensive measurement periods of the Carbo Europe Regional Experiment Strategy (CERES) campaign held in the South West of France.

Here we present the model validation for CO<sub>2</sub> and a wide range of meteorological fields obtained on surface and aircraft platforms during the campaign. In addition we have compared the modeled CO<sub>2</sub> concentration time series against observations at two towers operated during the campaign - Biscarosse (40 m high) and Bellegarde (56 m high) located in the vicinity of the coastline and inland respectively. The comparison against meteorological data reveals the ability of WRF to capture the small mesoscale flows which have also a strong impact on CO<sub>2</sub> measurements at the towers. This work shows how the near-field of these towers play an important role in the formation of the measured concentration signals. We also have investigated the vertical mixing of CO<sub>2</sub> by using different planetary boundary layer (PBL) parameterization schemes available in WRF. The results reveal that using more advanced PBL schemes within the high-resolution modeling framework enables us to better characterize the vertical distribution of CO<sub>2</sub>, especially in stable boundary layer during nighttime. Thus only with high resolution modeling tools such as WRF-VPRM can a large fraction of the CO<sub>2</sub> continuous data be properly used in inversion studies at the global and regional scales.

Finally we discuss the perspectives of WRF-VPRM applications for several North American CO<sub>2</sub> monitoring sites and measurement intensives operated by NOAA ESRL.



**Figure 1.** Comparison of hourly CO<sub>2</sub> concentration time series from the Biscarosse tower and the WRF-VPRM model.



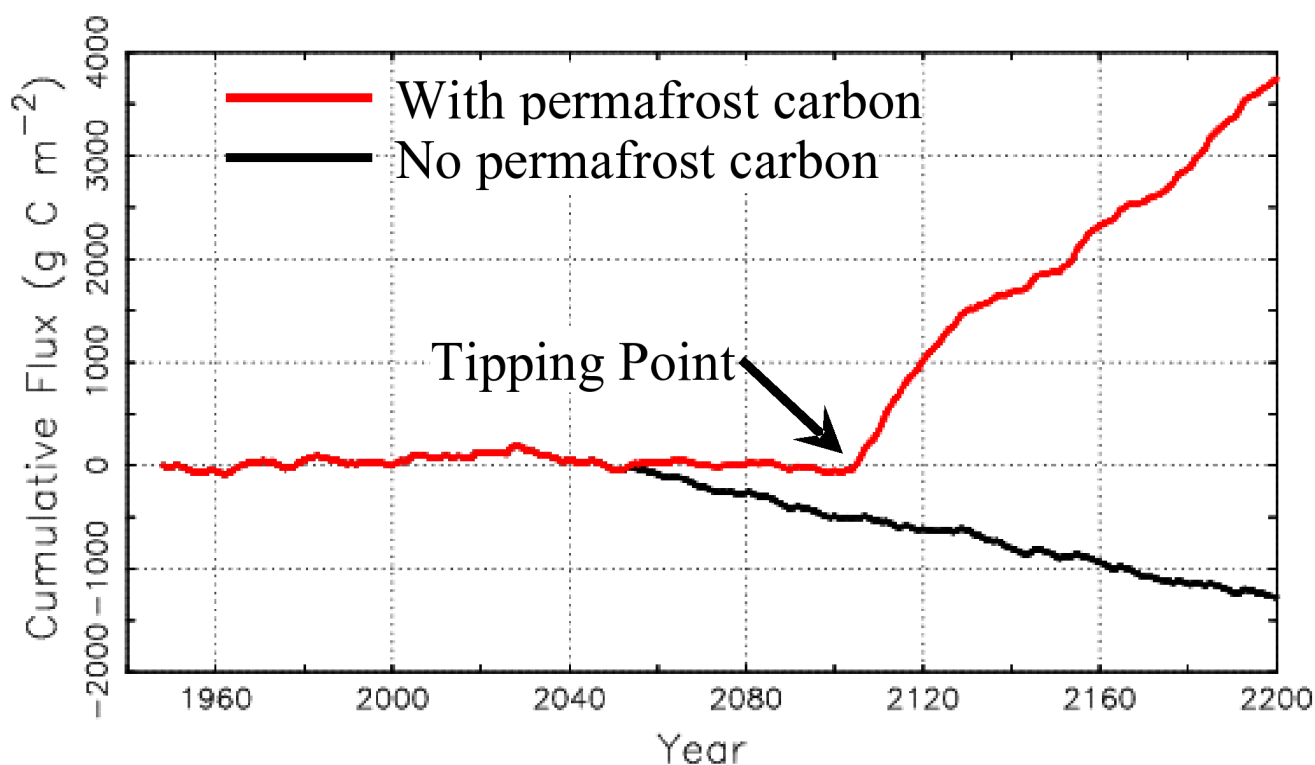
## When Is the Permafrost Carbon Tipping Point?

K. Schaefer<sup>1</sup>, T. Zhang<sup>1</sup> and L. Bruhwiler<sup>2</sup>

<sup>1</sup>National Snow and Ice Data Center, University of Colorado, Boulder, CO 80309; 303-492-8869, E-mail: kevin.schaefer@nsidc.org

<sup>2</sup>NOAA Earth System Research Laboratory, Boulder, CO 80305

Permafrost in the Arctic contains as much as 950 Gt of organic matter, frozen since the last ice age 20,000-30,000 years ago. As permafrost thaws in the 21<sup>st</sup> century, this organic matter will decay, increasing atmospheric carbon dioxide and amplifying the climate warming rate, creating a positive permafrost carbon feedback on climate. The permafrost carbon tipping point occurs when respiration due to the decay of thawed permafrost organic matter overpowers enhanced plant uptake due to longer growing seasons, changing the Arctic from a carbon sink to a source. The permafrost carbon tipping point represents an abrupt change in high latitude carbon balance and signals the start of the permafrost carbon feedback. None of the combined carbon-climate models used in the Fourth IPCC Assessment account for the permafrost carbon feedback in their projections of 21<sup>st</sup> century climate. We add permafrost carbon dynamics to the Simple Biosphere/Carnegie-Ames-Stanford Approach (SiBCASA) model and use the ERA40 reanalysis as input weather. To represent future climate change, we scale the ERA40 air temperature assuming a linear, 4 °C century<sup>-1</sup> temperature increase in the Arctic between 2000 and 2200. Point simulations indicate that even a modest increase in active layer depth could result in local tipping points by 2100. We expand this analysis to the entire Arctic region and estimate the timing of the permafrost carbon tipping point and the potential strength of the permafrost carbon feedback in terms of the amount of carbon released into the atmosphere by 2200.



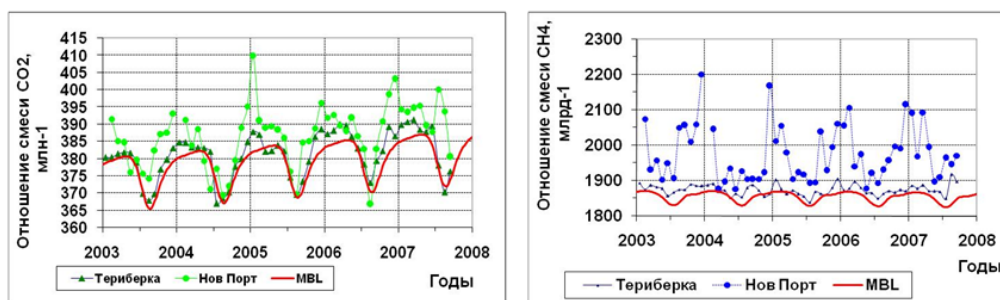
**Figure 1.** Cumulative simulated net carbon flux for a point in central Siberia (positive is net release to the atmosphere). The simulation without permafrost carbon (black) shows cumulative net uptake driven by longer growing seasons. The simulation with permafrost carbon shows a distinct tipping point in 2105 where respiration due to the decay of permafrost carbon overpowers the enhanced uptake due to longer growing seasons.

## Measurements of Greenhouse Gases in the Russian Arctic

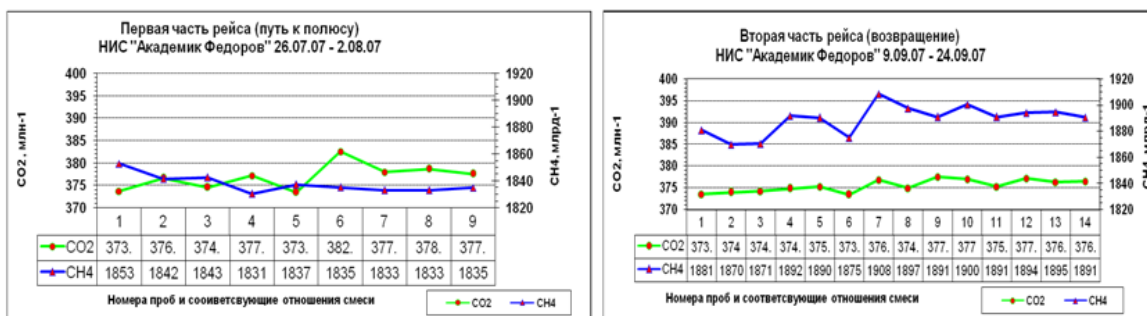
A.I. Reshetnikov, N.N. Paramonova, V.I. Privalov, A.V. Zinchenko and V.V. Ivachov

Main Geophysical Observatory, 7 Karbyshev Street, Saint Petersburg 194021, Russia; +8122978670, E-mail: alexR35@mail.ru

Carbon dioxide and methane are significant greenhouse gases and as such, large contributors to global warming. Russia covers about 17.8 million km<sup>2</sup> of land surface, much of it large expanses of boreal forests and tundra underlain by permafrost and large expanses of swamp land in West Siberia. In addition, extensive natural gas and oil deposits and extraction operations in the high Arctic have great potential to influence local and global atmospheric concentrations of carbon dioxide and methane. Below are presented the results of GHG measurements at the Russian Arctic stations Teriberka (69° 12' N, 35° 06' E) and New Port (67° 42' N, 72° 51' E) during 2003-2008, and data from the “Akademik Fedorov” ship route in the Arctic ocean during IPY cruises in 2007 - 2008. In Fig 1a are presented monthly CO<sub>2</sub> concentrations from the New Port and Teriberka Stations, and global MBL values from NOAA data. The large amplitude of the mixing ratio in the Russian station measurements most likely reflect the oil and gas burning in oil fields located about 1000 km to south. In Fig 1b are presented similar data for methane. The large amplitude of the methane mixing ratio are likely caused by both natural leaks and production in gas deposits located 80 – 250 km to the South. Data from GHG flasks sampled during the “Akademik Fedorov” transects up to the North Pole are represented in Fig 2a, and data from GHG flasks sampling during a transect from the Western Russian Arctic to Murmansk are presented in Fig 2b.



**Figure 1.** a) Monthly CO<sub>2</sub> mixing ratios at the New Port and Teriberka Stations and in the global MBL. The large amplitude of CO<sub>2</sub> mixing ratio observed at New Port is likely caused by the oil and gas burning in fields located about 1000 km to the south, b) Monthly CH<sub>4</sub> concentrations at the same station are likely caused by CH<sub>4</sub> leakage from a large gas field.



**Figure 2.** Data for flask sampling analysis at two parts of the “Akademik Fedorov” ship route: a) Arctic Coast to the North Pole, and b) In the Arctic ocean from 180 degrees west to Murmansk.



## Development of the FIM (Flow-Following Finite Volume Icosahedral Model) Global Model Toward an Earth System Model Including Inline Treatment of Aerosols and Trace Gases

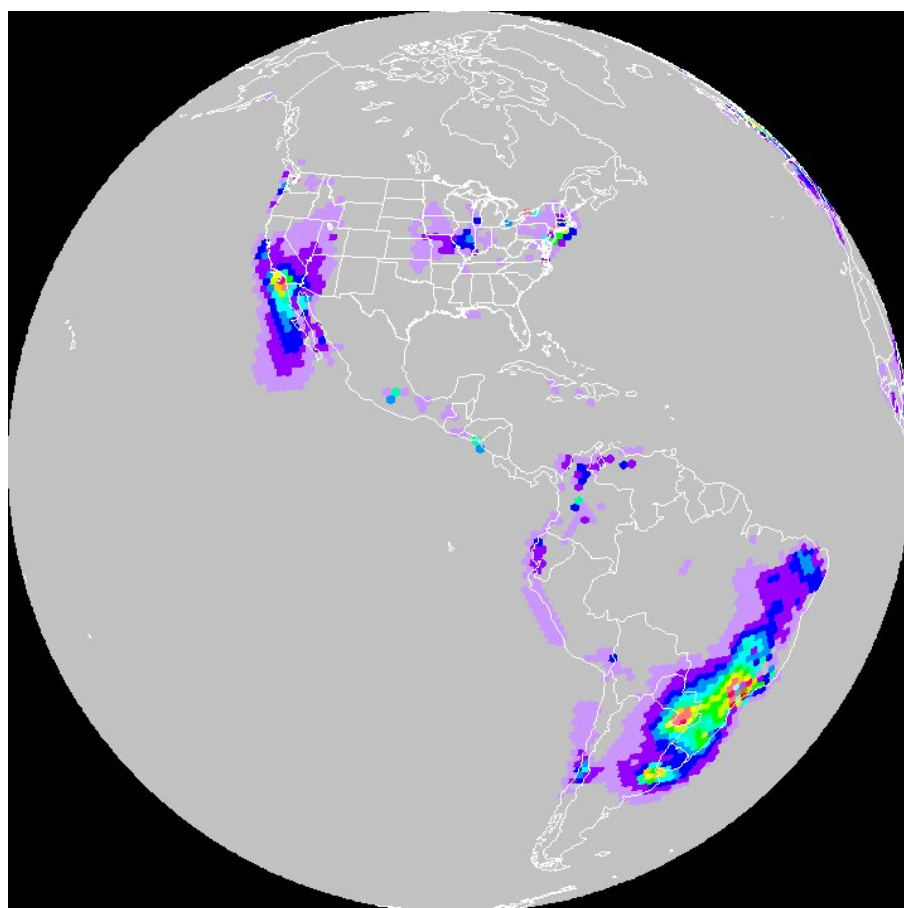
S.G. Benjamin<sup>1</sup>, G.A. Grell<sup>2</sup>, R. Bleck<sup>2</sup>, J.L. Lee<sup>1</sup>, J.W. Bao<sup>1</sup>, T.G. Smirnova<sup>2</sup>, J.M. Brown<sup>1</sup>, T.B. Henderson<sup>3</sup>, J.F. Middlecoff<sup>3</sup>, C.W. Harrop<sup>2</sup>, N. Wang<sup>3</sup>, A.E. MacDonald<sup>1</sup> and A.R. Jacobson<sup>2</sup>

<sup>1</sup>NOAA Earth System Research Laboratory, 325 Broadway, Boulder, CO 80305; 303-497-6387, E-mail: stan.benjamin@noaa.gov

<sup>2</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309

<sup>3</sup>Cooperative Institute for Research in Atmospheres, Colorado State University, Ft Collins, CO 80521

Development of the FIM, ESRL's new global model, is now being extended beyond medium-range weather forecasts to include aerosols and trace gases. The FIM uniquely combines 3 key modeling design components (icosahedral horizontal grids, isentropic-hybrid vertical coordinate, finite volume numerics), all critical to provide improved transport over existing models (e.g. Global Forecast System – GFS). The isentropic-hybrid vertical coordinate is “flow-following” in that the vertical coordinate surfaces follow isentropic (constant potential temperature) surfaces through most of the atmosphere, from mid-troposphere upward to the model top (current testing at ~60 km). This design greatly reduces cross-coordinate transport and resulting artificial numerical dispersion over that in most other atmospheric models. Atmospheric forecasts from the FIM now generally match those from the NCEP GFS model, necessary for planned inclusion of FIM as part of NCEP's Global Ensemble Forecast System. The FIM-chem inline coupled model is now in development, starting with a simple aerosol model from the GOCART including a global emissions inventory. (demo FIM-chem 3-day forecast in figure below). ESRL scientists from all four divisions are planning toward extension of FIM-chem to add trace gases, and also working toward a possible ocean component, and new land-surface, cloud, and boundary-layer parameterizations. This gives FIM potential for becoming an Earth Systems Model research tool, as well as having a real-time prediction capability.



**Figure 1.** 3-day forecast of organic carbon aerosol at approximately 120 hPa above surface from preliminary FIM-chemistry global model developed in ESRL.

# The Temporal and Spatial Distribution of Carbon Dioxide Emissions from Fossil-Fuel Use in North America

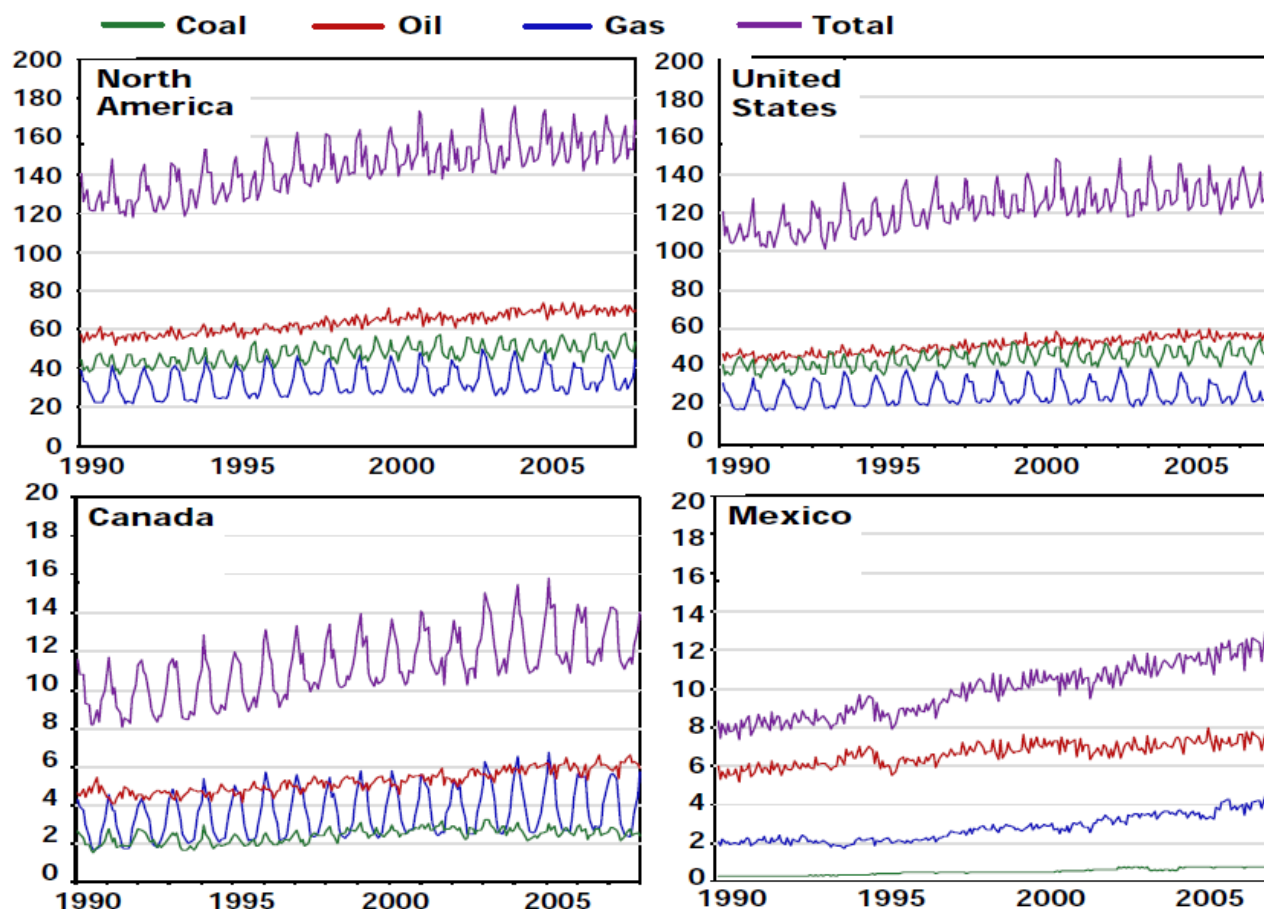
J.S. Gregg<sup>1</sup>, L.M. Losey<sup>2</sup>, R.J. Andres<sup>3</sup>, T.J. Blasing<sup>3</sup> and G. Marland<sup>3</sup>

<sup>1</sup>Department of Geography, University of Maryland, College Park, MD 20742

<sup>2</sup>Department of Space Studies, University of North Dakota, Grand Forks, ND 58202

<sup>3</sup>Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN 37831

Refinements in temporal and spatial resolution of North American fossil-fuel carbon dioxide (CO<sub>2</sub>) emissions provide additional information about anthropogenic aspects of the carbon cycle. Seasonal and spatial patterns are distinctive components of anthropogenic carbon emissions. The pattern of fossil-fuel-based CO<sub>2</sub> emissions on a monthly scale has greater temporal and spatial variability than the flux aggregated to the national annual level. The U.S. comprises the majority of North American fossil carbon emissions and the amplitude of the seasonal flux in emissions in the U.S. is greater than the total mean monthly emissions in both Canada and Mexico. Nevertheless, Canada and Mexico have distinctive seasonal patterns. For the continent, the monthly pattern of emissions vary on a both north-south and east-west gradient, and evolve through time. For many areas in North America, the magnitude of the month-to-month variation is larger than the total annual emissions from land use change, making the characterization of emissions patterns essential to understanding humanity's influence on the carbon cycle.



**Figure 1.** Monthly fossil fuel carbon emissions for North America, the U.S., Canada, and Mexico, by fuel type. Note that Canada and Mexico plots use a y-axis different from the one used for the North America and the U.S.

## Vertical Profiles of CO<sub>2</sub>, CH<sub>4</sub> and Other Trace Gases Above the Brazilian Amazon

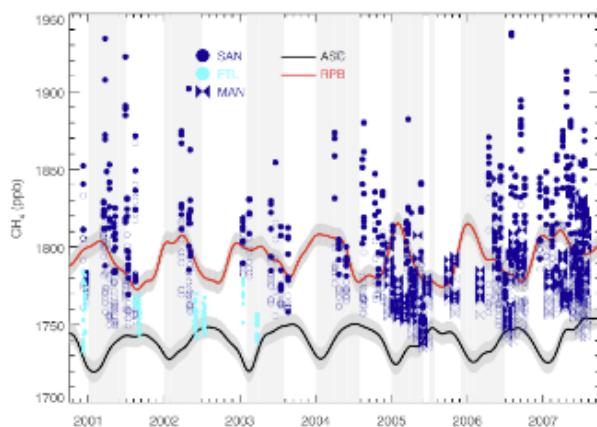
J.B. Miller<sup>1</sup>, L.V. Gatti<sup>2</sup>, M.T.S. Felipe<sup>2</sup>, P.P. Tans<sup>3</sup> and A. Crowell<sup>1</sup>

<sup>1</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309; 303-497-7739, E-mail: john.b.miller@noaa.gov

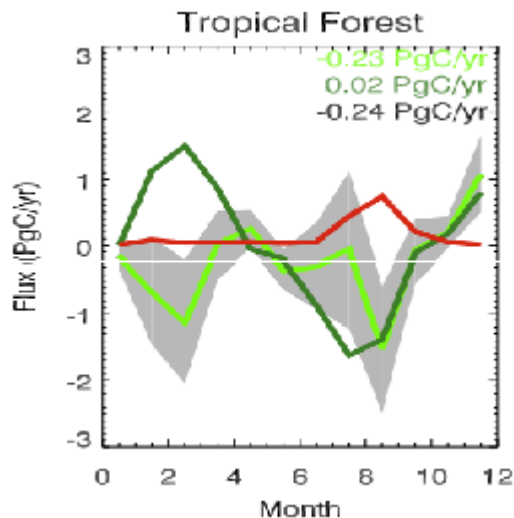
<sup>2</sup>Instituto de Pesquisas Energeticas e Nucleares (IPEN), Sao Paulo, Brazil

<sup>3</sup>NOAA Earth System Research Laboratory, Boulder, CO 80305

Since 2004, the NOAA ESRL Global Monitoring Division (GMD) has engaged in a very active collaboration with the IPEN Atmospheric Chemistry Laboratory focused on analyzing air samples collected above the Brazilian Amazon. The Amazon basin is both one of the most poorly sampled regions of the globe and at the same time one of the most critical to understand present day global greenhouse gas budgets and future climate feedbacks. In order to better study Amazonian greenhouse gas budgets, a copy of the GMD high precision, well-calibrated greenhouse gas analysis system (MAGICC) was built and installed at IPEN in April 2004. Between 2004 and 2008, more than 1500 samples have been collected above two sites in eastern and central Amazonia. These samples have been analyzed for CO<sub>2</sub>, CH<sub>4</sub>, CO, H<sub>2</sub>, N<sub>2</sub>O and SF<sub>6</sub> mole fractions. Our primary method of analysis has been to calculate the difference between the continental mole fractions and those measured in the tropical Atlantic by GMD at Ascension Island and Barbados. Using a simplified conception of atmospheric transport, we have calculated net surface fluxes between the coast and our sites. As can be seen in Figure 1, we see large enhancements of methane that translate to much larger fluxes than previously believed. In addition to the simplified flux calculations, we have also used regional and global inverse models to calculate surface fluxes. A flux calculation for CO<sub>2</sub> using the CarbonTracker inverse model is shown in Figure 2. The addition of the Amazonian observations substantially changes both the shape of the seasonal cycle and the annual net carbon flux, relative to the standard CarbonTracker results. The collaboration between NOAA and IPEN has proved very fruitful and has provided a unique dataset with which to analyze Amazonian greenhouse gas budgets.



**Figure 1.** CH<sub>4</sub> above Amazonian sites (blue symbols) compared to Atlantic background sites (black and red lines, with gray uncertainty bands). Vertical gray bars indicate wet season months near Santarem (SAN). Filled and empty symbols are those below and above 1500m, respectively.



**Figure 2.** Net CO<sub>2</sub> flux in CarbonTracker's South America Tropical Forest region, before (dark green) and after (light green) including data from SAN (for 2007). The red curve is the unoptimized biomass burning flux, and the gray error band represents statistical uncertainty of the flux result.

## Is Atmospheric Methane on the Rise Again?

E. Dlugokencky<sup>1</sup>, P. Lang<sup>1</sup>, K. Masarie<sup>1</sup>, A. Crotwell<sup>2</sup>, L. Bruhwiler<sup>1</sup>, L. Emmons<sup>3</sup>, S. Montzka<sup>1</sup> and J. White<sup>4</sup>

<sup>1</sup>NOAA Earth System Research Laboratory, 325 Broadway, Boulder, CO 80305; 303-497-6228, E-mail: ed.dlugokencky@noaa.gov

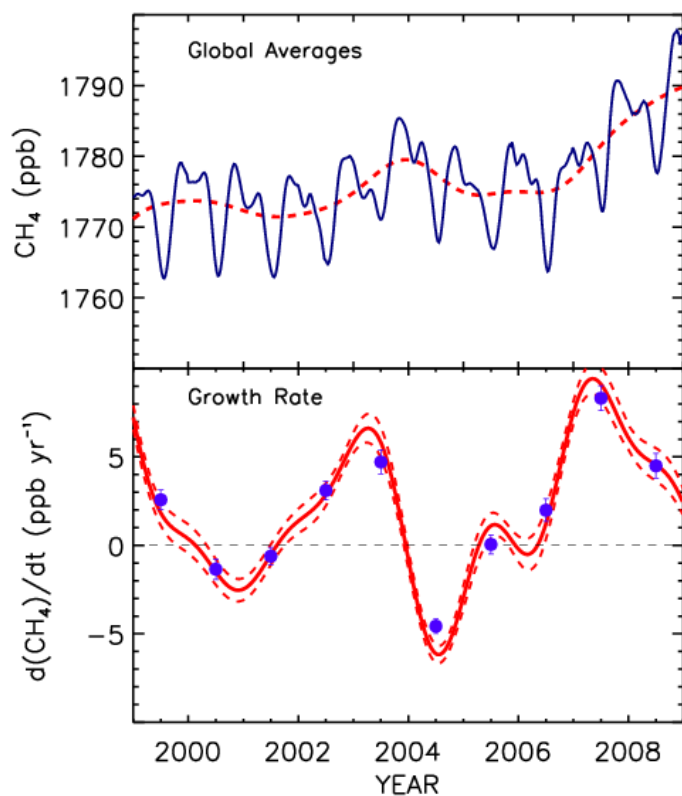
<sup>2</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309

<sup>3</sup>National Center for Atmospheric Research, Boulder, CO 80307

<sup>4</sup>Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO 80309

Methane ( $\text{CH}_4$ ) is the most important greenhouse gas influenced by human activities after  $\text{CO}_2$ . Its chemistry results in additional indirect climate effects from production of tropospheric  $\text{O}_3$ , which also affects air quality, and stratospheric  $\text{H}_2\text{O}$ . Natural emissions of  $\text{CH}_4$ , from Arctic wetlands and hydrates, are susceptible to changing climate, and they have the potential to cause strong positive climate feedbacks.

From 1999 to 2006, the global burden of atmospheric  $\text{CH}_4$  remained nearly constant (see Figure), except for a small increase resulting from increased boreal biomass burning during 2002 and 2003. Since 2006, globally averaged  $\text{CH}_4$  increased by  $\sim 13$  ppb. Does this increase signal the start of increased emissions in the Arctic from permafrost or hydrates because of warming climate, or is it from increased emissions from coal production and waste processing in rapidly growing economies in Asia? We suspect it is neither.



**Figure 1.** Preliminary globally averaged  $\text{CH}_4$  mole fractions (blue) and trend (red) (top panel); instantaneous growth rate (red) and annual increase (blue) (bottom panel).

During 2007, globally averaged  $\text{CH}_4$  increased by 8.3 ppb. High northern latitudes and the tropics showed the largest increases. The increase in  $\text{CH}_4$  at high northern latitudes was accompanied by lower than average  $\delta^{13}\text{C}$  in  $\text{CH}_4$  from Alert, Canada during late-summer, which suggests greater than normal  $\text{CH}_4$  emissions from wetlands. While NOAA surface  $\text{CO}$  data from the same samples analyzed for  $\text{CH}_4$  suggest little potential contribution to the increase in  $\text{CH}_4$  from biomass burning, MOPITT (Measurements Of Pollution In The Troposphere) observed positive  $\text{CO}$  anomalies up to  $\sim 90$  ppb at 700 hPa during late-2006 over SE Asia. These signals may not have been observed at NOAA surface sites, because our sites may not be properly positioned to sample them.

During 2008,  $\text{CH}_4$  at high northern latitudes remained at approximately 2007 levels, but a significant increase in  $\text{CH}_4$  was observed in the tropics. Globally,  $\text{CH}_4$  increased by 4.5 ppb. The causes of this increase are not clear, but La Niña conditions were observed starting in mid-2007, waned somewhat during late-2007, and then intensified during 2008. These conditions often have increased precipitation associated with them in SE Asia and eastern Amazonia. Increased precipitation would have resulted in increased emissions from tropical wetlands, the largest  $\text{CH}_4$  source in the global budget. Other potential contributors are increased inter-hemispheric exchange, which would increase SH  $\text{CH}_4$ , and changes in  $[\text{OH}]$  that affect the  $\text{CH}_4$  lifetime.

## AGAGE and CSIRO Measurements of Recent Global Methane Growth

M. Rigby<sup>1</sup>, R. Prinn<sup>1</sup>, P. Fraser<sup>2</sup>, P. Simmonds<sup>2</sup>, J. Huang<sup>1</sup>, R. Langenfelds<sup>2</sup>, D. Cunnold<sup>3</sup>, P. Steele<sup>2</sup>, P. Krummel<sup>2</sup>, R. Weiss<sup>4</sup>, S. O'Doherty<sup>5</sup>, P. Salameh<sup>4</sup>, H. Wang<sup>3</sup>, C. Harth<sup>4</sup>, J. Mühle<sup>4</sup> and L. Porter<sup>6</sup>

<sup>1</sup>Center for Global Change Science, Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, MA 02139; 617-258-0838, E-mail: mrigby@mit.edu

<sup>2</sup>Centre for Australian Weather and Climate Research, CSIRO Marine and Atmospheric Research, Aspendale, Victoria, Australia

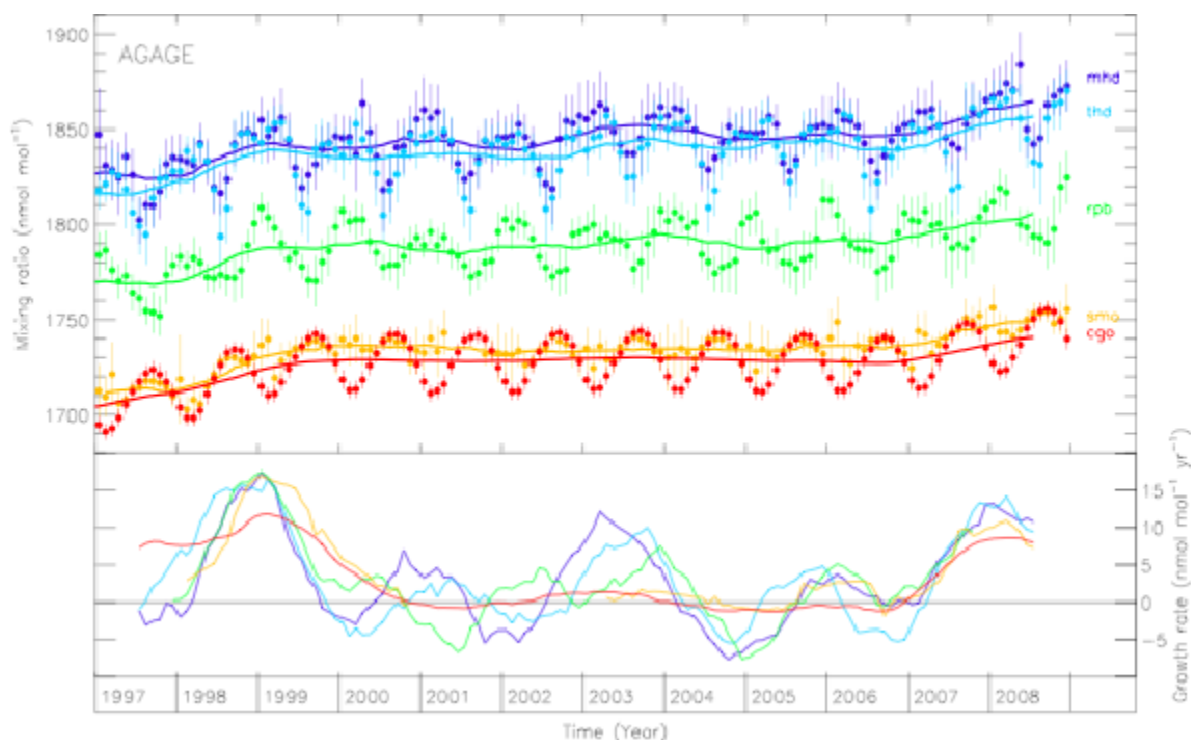
<sup>3</sup>School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA 30332

<sup>4</sup>Scripps Institution of Oceanography, University of California at San Diego, La Jolla, CA 92093

<sup>5</sup>School of Chemistry, University of Bristol, Bristol, United Kingdom

<sup>6</sup>Australian Government Bureau of Meteorology, Melbourne, Victoria, Australia

Measurements by the Advanced Global Atmospheric Gases Experiment (AGAGE) and the Commonwealth Scientific and Industrial Research Organization (CSIRO) show renewed growth of atmospheric methane from early 2007 to present. This rise follows almost a decade of relatively stable global methane levels and has occurred at all monitoring locations almost simultaneously. A two-dimensional model of atmospheric chemistry and transport is used to optimally estimate the increase in emissions required to produce such a rise. If annually repeating hydroxyl radical concentrations are assumed, we find that emissions rose by similar levels in both hemispheres during 2007. The 2007 global emissions were found to be elevated by approximately 25Tg/yr compared to the 10-year average. Mean emissions during 2008 were estimated to be lower than in 2007, but still higher than the average (by approximately 15Tg/yr), with the Northern hemisphere accounting for most of the 2008 emissions anomaly.



**Figure 1.** AGAGE monthly baseline methane mole fraction, January 1997 to December 2008 measured at Mace Head, Ireland (mhd), Trinidad Head, California (thd), Ragged Point, Barbados (rpb), Cape Matatula, American Samoa (smo) and Cape Grim, Tasmania (cgo). The thick line in the upper panel shows the annual running mean mole fraction. The lower panel shows the annual average growth rate at each site. Error bars and growth rate are calculated as in Rigby et al. (2008) Renewed Growth of Atmospheric Methane, *Geophys. Res. Lett.*, 35, L22805.



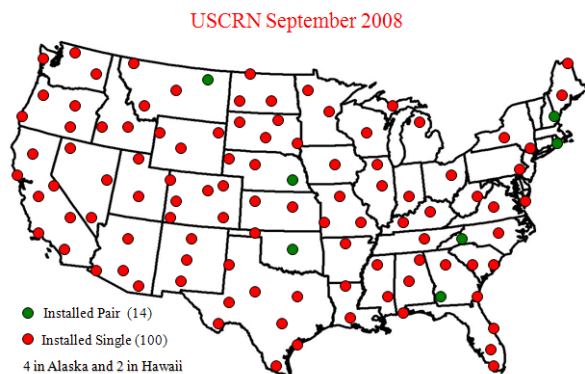
## U.S. Climate Reference Network: Current Status and Future Directions

S. LeDuc and M. Palecki

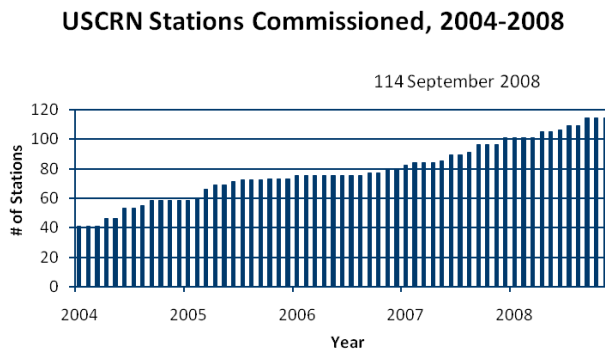
National Climatic Data Center, 151 Patton Ave., Asheville, NC 28801; 828-271-4848, E-mail: sharon.leduc@noaa.gov

The USCRN deployment in the continental U.S. was completed in September 2008, with a network of 114 stations at 107 locations (Figure 1). This spatial distribution is sufficient to explain 98% of the variance of the annual U.S. temperature average and 95% of the variance of the annual U.S. precipitation total. The locations were chosen with great care at very stable sites that are intended to remain rural and unchanged for the next 50-100 years. Therefore, between the site selection and the science-based observation techniques adhering to the best principles for climate observation, the USCRN climate records will not be required to be homogenized going forward, providing a premier time series record of national climate change as it occurs. The USCRN will also be valuable for climate monitoring from daily to annual scales, providing accurate assessments of climate extremes, cumulative variables such as heating and cooling degree days, and, in the near future, high-quality soil moisture and soil temperature observations. A deployment of 30 USCRN stations to Alaska is in progress, and the impending rollout of the USHCN-M regional climate change pilot project in the Southwest is based on USCRN practices.

Early observations from the first seven years of the USCRN will be examined to illustrate the value and utility of this science-based approach to climate observation. Triple configurations of both temperature sensors and precipitation gauge depth measurements insure data quality by providing independent measurements that can be cross-checked continuously, and also safeguard continuity against the failure or replacement of a single instrument. A new USCRN climate science project is beginning to take shape to supplement the ongoing instrumentation science work. Some of the near-term plans for this project will be presented, including the development of temperature and precipitation pseudo-normals, threading time series of historical observations to USCRN data, and exploring USCRN observations relevant to satellite and modeling calibration/validation. Outreach is taking place to encourage more use of USCRN observations in the climate stakeholder communities, and data access has been made easier for external users.



**Figure 1.** Location map for USCRN stations and network growth from 2004 to 2008 completion.



**Figure 2.** Time Series of Station Commissioning.

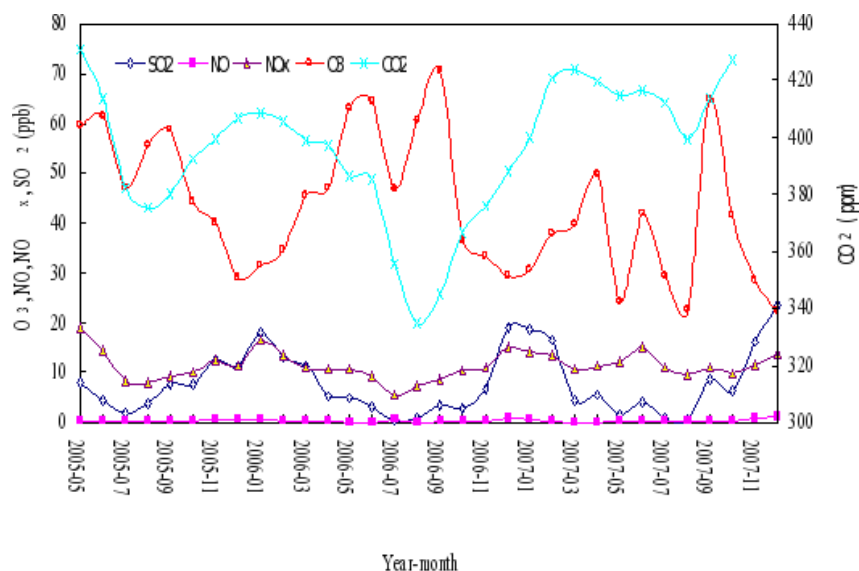
## Primary Study on the Characteristics of Trace Gases in a Clean Area of North China

B. Jianhui, W. Gengchen and W. Pucai

Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China; 86-10-82995079,  
E-mail: bjh@mail.iap.ac.cn

During 22 May, 2005 to 31 December, 2007, continuous measurements of some trace gases at Xinglong station (150 km northeast of Beijing city), atmospheric background observation network of Chinese Academy of Sciences were carried out. Some basic characteristics and variation regularities of  $O_3$ ,  $NO_x$  ( $NO$ ,  $NO_2$ ),  $CO_2$ ,  $SO_2$ , and their concentrations were obtained. In general,  $O_3$  displayed a higher concentration in June and September, and the lowest concentration in December.  $NO_x$  indicated the lowest concentration in August, and slowly increased during August to December, the ratio of  $NO$  to  $NO_x$  is very low.  $SO_2$  showed the lowest concentration in July, and then increased gradually.  $CO_2$  exhibited the lowest concentration in August. During September 10 to November 11 of 2005, solar spectral radiation was measured at Xinglong Station. UV radiation, the important energy source to control ozone production and depletion, displayed obvious diurnal and daily variations. Though UV and  $O_3$  have some similar diurnal and daily variations, no good correlation can be found between them during the period of September to November, which showed their relationship is complicated. In more detail, daily maximum of hourly averages of UV was earlier than that of  $O_3$  for most conditions, which indicated that UV energy is the triggering energy for  $O_3$  formation. In order to better understand  $O_3$  chemistry and photochemistry, solar radiation,  $O_3$  and its precursors of  $NO_x$ , VOCs (Volatile Organic Compounds), and aerosols should be measured synthetically.

Based on the measurements, good air quality at Xinglong Station is in July and August. Recently, the fast developments in industry, agriculture, economy and traffic in Beijing city and its surrounding cities will bring changes to trace gases in these areas. Xinglong Station can be considered as a good and unique atmospheric background station for the comprehensive study on solar radiation, atmospheric chemistry & photochemistry, aerosols (especially secondary organic compounds), and how and in what extent the human activities influence the atmospheric environments, solar radiation and its spectrum at the Earth's surface, and so on. Thus, it's important to carry out a long-term monitoring of trace gases, VOCs, solar radiation, aerosols, meteorological parameters, and study the basic physical and chemical & photochemical processes in the real atmosphere deeply and thoroughly, some unimportant processes may become more important than we thought before. Meanwhile, reliable and long-term integrated dataset is very valuable for models data input and models validation. So, the collaboration especially international collaboration is a better way for us to understand basic physical, chemical & photochemical processes in North China/different sites in the world.



**Figure 1.** Monthly variations of trace gas concentrations at XingLong Station.



## Overview of Chemical and Physical Measurements at Lulin Atmospheric Background Station (LABS, 2,862m MSL) in Taiwan, East Asia Since 2006

N.H. Lin<sup>1</sup>, J.L. Wang<sup>2</sup>, C.T. Lee<sup>3</sup>, G.R. Sheu<sup>1</sup> and S.H. Wang<sup>1</sup>

<sup>1</sup>Department of Atmospheric Sciences, National Central University, Chung-Li 320, Taiwan; +886-3-4254069, E-mail: nhlin@cc.ncu.edu.tw

<sup>2</sup>Department of Chemistry, National Central University, Chung-Li 320, Taiwan

<sup>3</sup>Graduate Institute of Environmental Engineering, National Central University, Chung-Li 320, Taiwan

The Lulin Atmospheric Background Station (LABS) in Taiwan held its grand opening for operation on 13 April 2006. It is located at the Mt. Lulin (2,862 m MSL; 23° 28'07"N, 120°52'25"E) in central Taiwan. The LABS is unique because its location and altitude can enhance the global network of GAW (Global Atmosphere Watch) in the Southeast Asian region where no high-elevation baseline station is available. Our site is located between the GAW Waliguan station (3,810 m) in Tibetan plateau and Mauna Loa Observatory (3,397m) in Hawaii.

Trajectory study indicates that this site provides us a great chance to observe a variety of air mass originated from contaminated or clear source regions, giving a distinctive contrast of atmospheric changes. Present continuous operations include precipitation chemistry, aerosol chemistry, trace gases (CO, O<sub>3</sub>, CFCs, VOCs), mercury, atmospheric radiation, and meteorological variables. Till present time, the average concentrations of CO, O<sub>3</sub> and PM10 are about 121 ppb, 34 ppb and 10 µg m<sup>-3</sup>, respectively. The average pH value of precipitation is 5.73. The average concentrations of mercury such as GEM, RGM and PHg are about 1.78 ng m<sup>-3</sup>, 41.65 pg m<sup>-3</sup> and 8.96 pg m<sup>-3</sup>, respectively. The average aerosol optical depth is 0.101. The background concentrations of CO, O<sub>3</sub> and PM10 are estimated to be about 82 ppb, 28 ppb and 6 µg m<sup>-3</sup>, respectively. About 32% of the days in a year can be defined to be polluted. Especially in March, the concentrations of above three pollutants show twice higher than their background values. To summarize the results, the maximum concentration of pollutants generally occurred during spring time, especially in March, corresponding to the biomass burning from SE Asia.



**Figure 1.** Lulin Atmospheric Background Station (LABS).

## Year-Round Measurements and Interpretations at Greenland Environmental Observatory at Summit (GEOSummit)

R. Banta<sup>1</sup>, J. McConnell<sup>1</sup>, T. Cahill<sup>2</sup>, J. Burkhardt<sup>3,4</sup> and R. Bales<sup>4</sup>

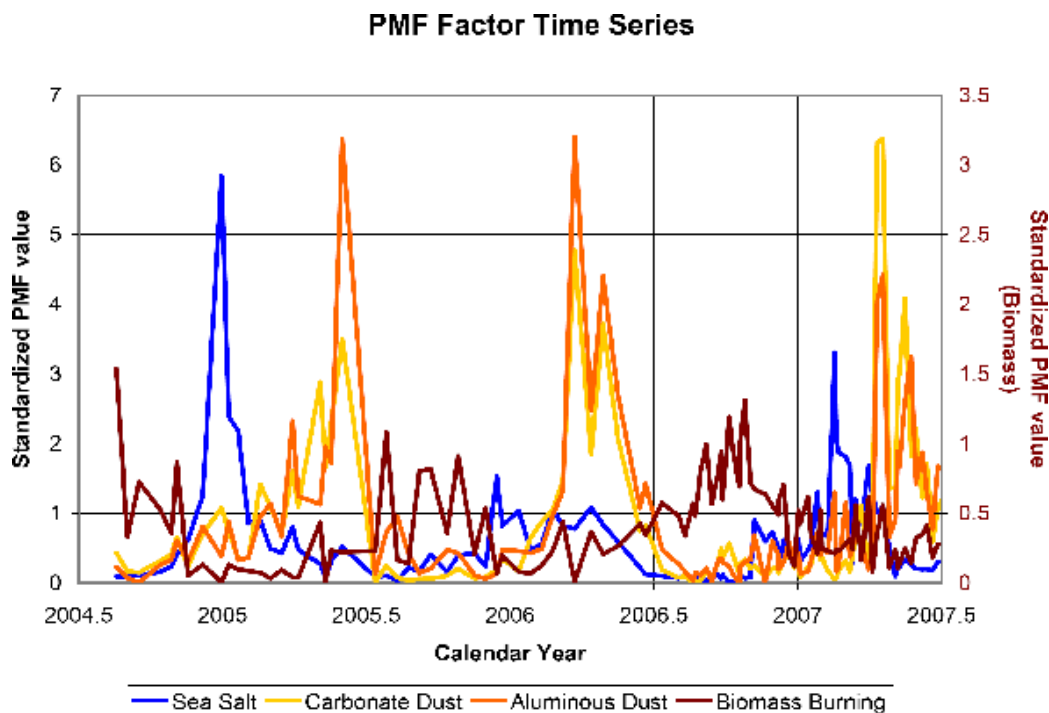
<sup>1</sup>Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512; 775-673-7442, E-mail: ryan.banta@dri.edu

<sup>2</sup>University of California at Davis, Davis, CA 95616

<sup>3</sup>Norwegian Institute for Air Research, Kjeller, Norway 2027, Norway

<sup>4</sup>University of California at Merced, Merced, CA 95343

Long-term year-round sampling of the Arctic atmosphere and surface snow provide insight to the relationship between aerosol and snow chemical compositions. Ongoing research at the Greenland Environmental Observatory, Summit Station (GEOSummit) includes high temporal resolution year-round measurements of snow accumulation and spatial variability, IC and ICP-MS trace-element measurements of surface-snow and snow-pit samples, DRUM aerosol size and S-XRF elemental composition, and other meteorological and snow properties. These measurements allow for a better understanding of the timing and magnitude of the seasonal cycles in elemental concentrations that are deposited and preserved in the snow pack, some of which have not been previously reported. These records were analyzed using a multivariate factor analysis model called Positive Matrix Factorization (PMF) to identify unique source factors representative of sea salt, dusts, and other potential sources such as biomass burning. These source factors exhibited distinct seasonal cycles with significant year-to-year variability. Snow accumulation rates were concurrently measured, thereby aiding the evaluation of wet and dry deposition as well as quantifying the inter-annual variability in snow accumulation. In addition, using the Lagrangian Particle Dispersion Model (LPDM) FLEXPART, source regions of specific events that transport pollution or dust from North America and/or Asia can be identified. Continuous longer-term records are necessary for evaluating links between aerosol and snow chemistry to geophysical processes with multi-year periodicities (e.g. AO, AMO, etc). Future plans include continuing research measurements at GEOSummit (5-yr continuation proposal submitted) to better characterize elemental concentrations in snow and aerosols, annual to decadal variability in snowfall, and connections with atmospheric circulation and transport.



**Figure 1.** Time series of PMF source factors attributed to sea salt, carbonate dust, aluminous dust, and biomass burning. Note the strong seasonality and inter-annual variability of the source factors.

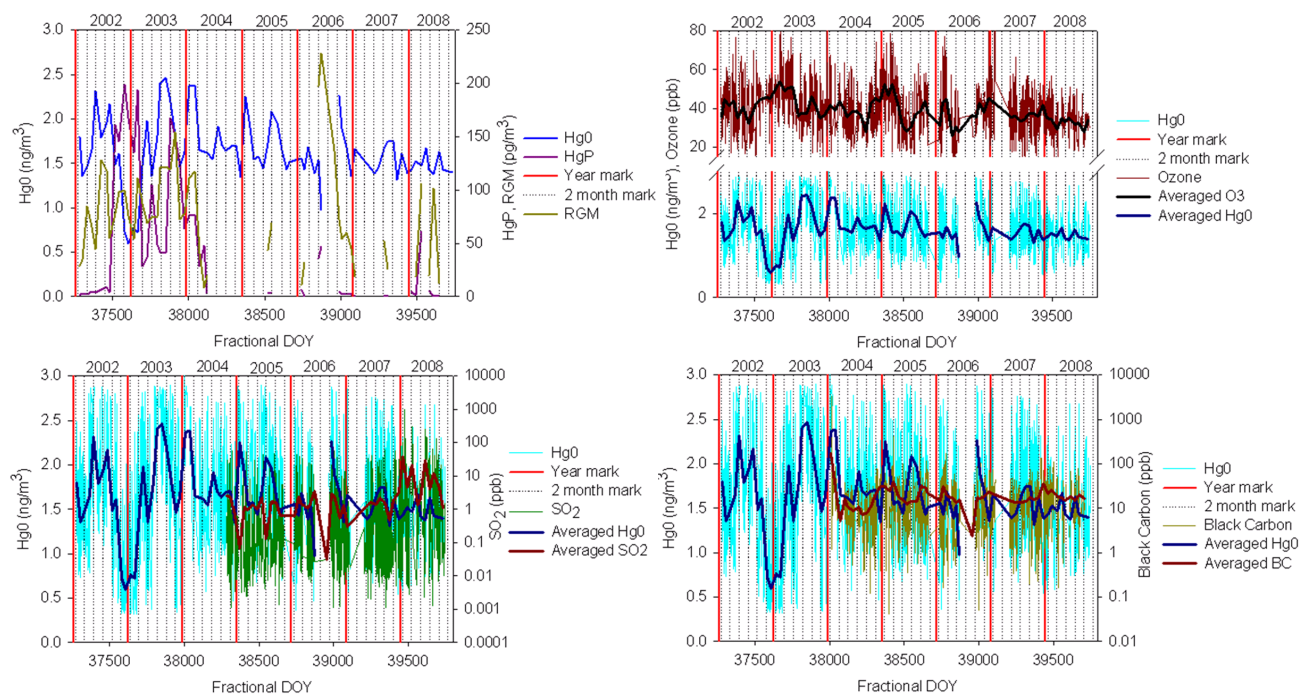
# Measurements of Ambient Mercury and Related Species at the Mauna Loa Observatory 2002-2008

L. Alvarez-Aviles<sup>1</sup>, M.S. Landis<sup>1</sup>, D. Kuniyuki<sup>2</sup> and A. Colton<sup>1,2</sup>

<sup>1</sup>U.S. Environmental Protection Agency, 109 T.W. Alexander Drive, Research Triangle Park, NC 27711; 919-541-3330, E-mail: Alvarez-Aviles.Laura@epamail.epa.gov

<sup>2</sup>NOAA Earth System Research Laboratory, Mauna Loa Observatory, Hilo, HI 96720

EPA ORD and NOAA ESRL initiated measurements of gaseous elemental mercury ( $\text{Hg}^0$ ), divalent reactive gaseous mercury (RGM), and particulate bound mercury ( $\text{Hg}(\text{p})$ ) in 2002 at the Mauna Loa Observatory (MLO). Collocated elemental carbon,  $\text{O}_3$  and  $\text{SO}_2$  measurements were subsequently initiated in 2004. NOAA ESRL  $\text{O}_3$  data was used to complete our data set from 2002 - 2004.  $\text{Hg}^0$  concentrations ranged between 0.3 and 2.9  $\text{ng m}^{-3}$ , and average  $\pm$  standard deviation was  $1.6 \pm 0.5 \text{ ng m}^{-3}$ ;  $\text{Hg}(\text{p})$  concentrations ranged between 1 - 1900  $\text{pg m}^{-3}$ , and RGM ranged between 0.6 - 360  $\text{pg m}^{-3}$ . Periods when  $\text{Hg}(\text{p})$  is anti-correlated to  $\text{Hg}^0$  are also periods when ozone is anti-correlated to  $\text{Hg}^0$  (2002 - 2003), suggesting that air masses sourcing ozone differ from that of  $\text{Hg}^0$ , possibly of stratospheric origin. The majority of  $\text{SO}_2$  impacting Mauna Loa is expected to be of volcanic origin.  $\text{SO}_2$  correlation with  $\text{Hg}^0$  suggests that we observed significant  $\text{Hg}^0$  during periods of volcanic activity, while anti-correlation periods indicate long distance transport influences for  $\text{Hg}^0$  in contrast to the more regional volcanic influences for  $\text{SO}_2$ . Elemental carbon is a good indicator of anthropogenic sources and is mostly correlated to  $\text{Hg}^0$ , suggesting that most  $\text{Hg}^0$  observed at MLO is of anthropogenic origin. This study is still in early stages of data analysis and validation, a complete presentation of the data and detailed analysis will be presented.



**Figure 1.**  $\text{Hg}^0$ ,  $\text{HgP}$ , RGM, ozone,  $\text{SO}_2$  and black carbon concentration trends in Mauna Loa, Hawaii in 2002 – 2008. The solid thick lines represent the monthly average and the lighter solid line is the 3 hour resolution measurement for the chemical species.



# Interpreting Total Gaseous Mercury Observations with Lagrangian and Eulerian Atmospheric Models: A Canadian Perspective

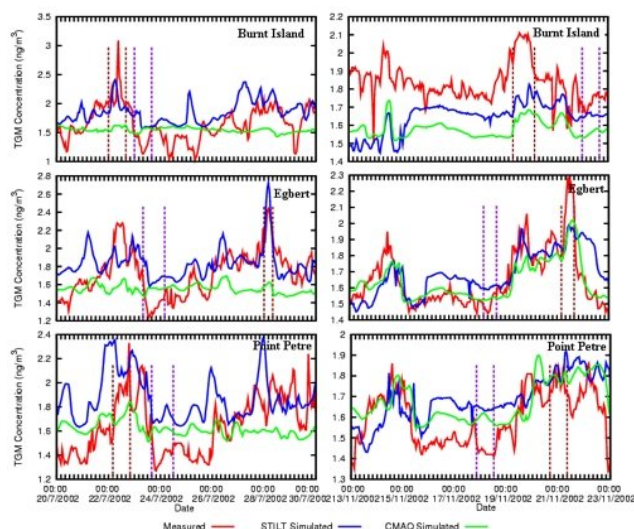
J.C. Lin, D. Wen and J.J. Sloan

University of Waterloo, 200 University Ave. W, Waterloo, ON N2L3G1, Canada; 519-888-4567x3325, E-mail: jcl@uwaterloo.ca

Total gaseous mercury (TGM) concentrations at monitoring sites in Canada were simulated using the Stochastic Time-Inverted Lagrangian Transport (STILT) model. The model was modified in this work to deal with Hg depositions and high stack Hg emissions. The model-predicted Hg concentrations were compared with observations, as well as with the results from an Eulerian-based (CMAQ) simulation, in which the same emission and meteorology inputs were used. The comparisons show that STILT predicted Hg concentrations show better agreement with observations than those predicted by CMAQ. Furthermore, Fourier spectra indicated that high-frequency variability in the Eulerian model was severely damped while captured by the Lagrangian approach, due to the latter's ability to account for near-field influences. STILT was also applied to quantitatively assess relative importance of different upstream source regions for the selected episodes. The results indicated that the substantial source regions of the observed low Hg concentrations were some nearby cities and towns in Northeastern Ontario, and that elevated observations at three sites were mainly due to the contributions of significant point sources and areas in Southern Ontario, Ohio, Virginia and Michigan. Additionally, this work has illustrated the potential of STILT to interpret and identify source regions of pollutants in the future.



**Figure 1.** Locations of the three monitoring sites: Burnt Island, Egbert and Point Petre.



**Figure 2.** Total Gaseous Mercury (TGM) concentration comparisons among observed (red), STILT modeled (blue), and CMAQ-modeled (green) for two simulation periods: Jul 20-29 (right) and Nov 13-22 (left), 2002 for Burnt Island (top), Egbert (middle) and Point Petre (bottom).

# Measurements of the Stable Isotopologues of Water Vapor at Mauna Loa for Monitoring the Atmospheric Water Cycle

D. Noone<sup>1</sup>, J. Galewsky<sup>2</sup>, J. Barnes<sup>3</sup>, Z. Shark<sup>2</sup>, D. Toohey<sup>4</sup> and J. Worden<sup>5</sup>

<sup>1</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309; 303-735-6073, E-mail: dcn@colorado.edu

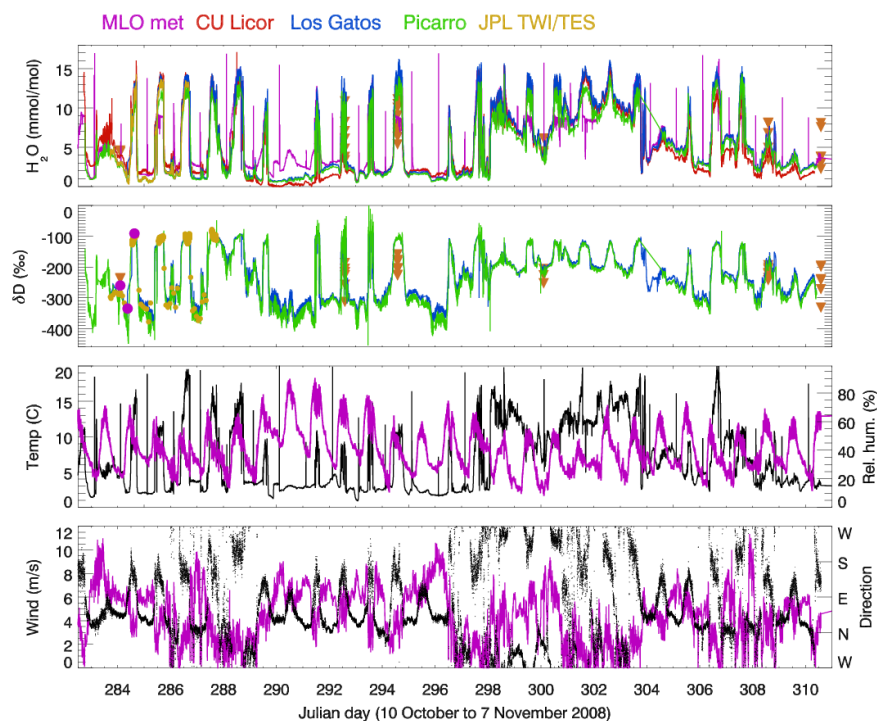
<sup>2</sup>Department of Earth and Planetary Science, University of New Mexico, Albuquerque, NM 87131

<sup>3</sup>NOAA Earth System Research Laboratory, Mauna Loa Observatory, Hilo, HI 96720

<sup>4</sup>Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder, CO 80309

<sup>5</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CO 91109

Measurements of the isotopic composition of water vapor reflect the history of air mass mixing and cloud processes influencing the vapor as it moves through evaporation and transpiration. This comes about because heavy isotopologues of water (i.e, HDO and H<sub>2</sub><sup>18</sup>O) have a different vapor pressure than normal (lighter) H<sub>2</sub>O, and as such they prefer to remain in the condensed phase during both condensation and evaporation. Continuous measurements of H<sub>2</sub>O, H<sub>2</sub><sup>18</sup>O and HDO were made at Mauna Loa for four weeks in October 2008 using three laser-based spectroscopic analyzers. Figure 1 shows that at Mauna Loa the isotopic composition dramatically captures the dramatic diurnal transition between air influenced by the marine boundary layer during day and free troposphere air at night. Closer examination shows that this transition is almost reversible, yet the isotopic signature of clouds is evident and suggests cloud processes play a role in the energy budget that maintains the MBL. The very dry and isotopically depleted free-troposphere air indicates that the humidity is set though ice cloud processes either in the midlatitudes or in the upper troposphere within the Inter-Tropical Convergence Zone. Moistening of the troposphere near Mauna Loa occurs in association with detrainment from warm convection, as is exemplified by an “atmospheric river” event that was observed in the second half of the field period. This work establishes that commercially available isotopic vapor analyzers are both capable of monitoring the isotopic composition at NOAA baseline stations, that the calibrated measurements are of remarkable high precision, and that the data can be used to establish new understanding of the atmospheric water cycle.



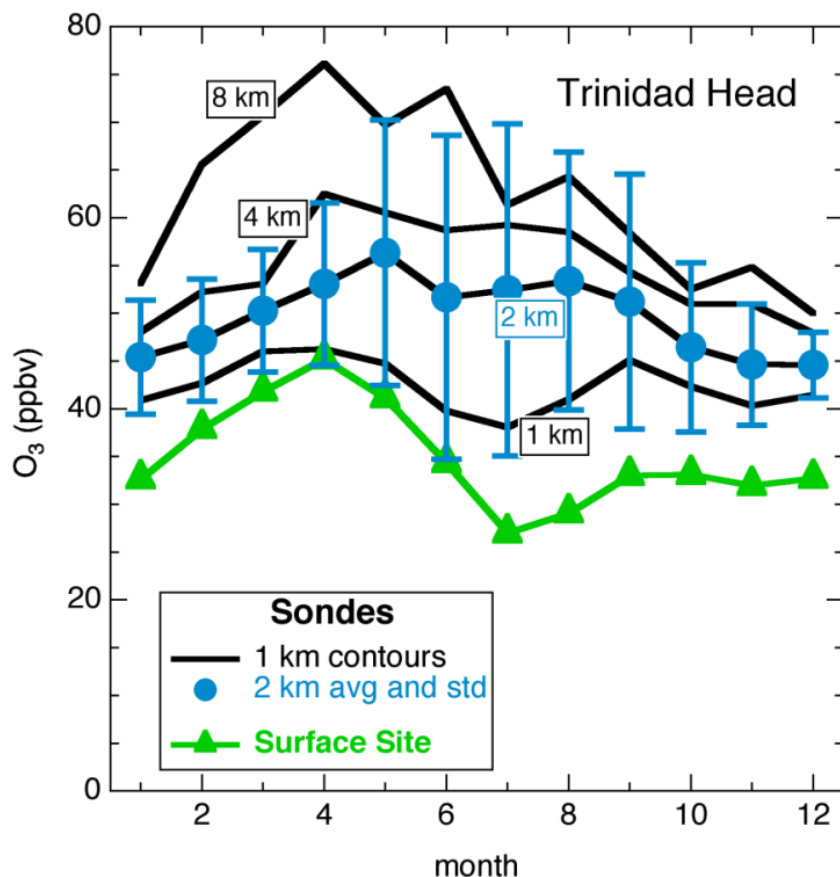
**Figure 1.** Time series of a) water vapor volume mixing ratio, b) dD of water vapor c) station temperature (magenta) and relative humidity (black) and d) wind speed (magenta) and direction (black dots) at Mauna Loa from 10 October to 6 November 2008. Panel a and b include all observations from station meteorological dew point hygrometer (magenta), Licor 7000 IRGA (red), LGR WVIA (blue), Picarro IWVA (green), JPL-TWI (orange circles), TES satellite FTIR (gold triangles) and 3 flasks (magenta circles).

## Air Quality Implications of Ozone in Air Entering the West Coast of North America

D.D. Parrish, K.C. Aikin, S.J. Oltmans and B.J. Johnson

NOAA Earth System Research Laboratory, 325 Broadway, Boulder, CO 80305; 303-497-5274, E-mail: David.D.Parrish@noaa.gov

Ozone measurements conducted by the Global Monitoring Division at Trinidad Head, California provide a unique opportunity to evaluate the impact that background ozone transported ashore has on air quality over the North American continent. The northern Sacramento Valley lies  $\approx 160$  km inland from Trinidad Head. This valley is designated as a non-attainment area for the California state ozone standard, and the observed maximum mixing ratios indicate that the area will also violate the new 75 ppbv National Ambient Air Quality Standard (NAAQS). Figure 1 shows that the summertime surface air flowing ashore from the Pacific Ocean carries average ozone mixing ratios of  $\approx 30$  ppbv, which are well below the NAAQS. However, in summer (the season of the highest ozone in inland areas) there is a strong vertical gradient in ozone. The average ozone at 2 km altitude exceeds 50 ppbv, and one standard deviation above the average exceeds 70 ppbv. Thus, if air from 2 km altitude were mixed to the surface of the northern Sacramento Valley, the transported background ozone would significantly affect the surface ozone. The coastal mountain range separates the valley from the marine environment and its crest is at elevations of  $\geq 1$  km, so such mixing is expected. We will use correlations between the Trinidad Head sonde data and northern Sacramento Valley surface site data to show that such downward mixing does indeed occur, and we will argue that background ozone alone is sufficient for NAAQS violations. If correct, the implications of this conclusion are profound. Local or state efforts will not be adequate to achieve the NAAQS for ozone, at least in the northern Sacramento Valley. Additional international efforts to reduce background ozone at northern mid-latitudes will be required for effective control of violations.



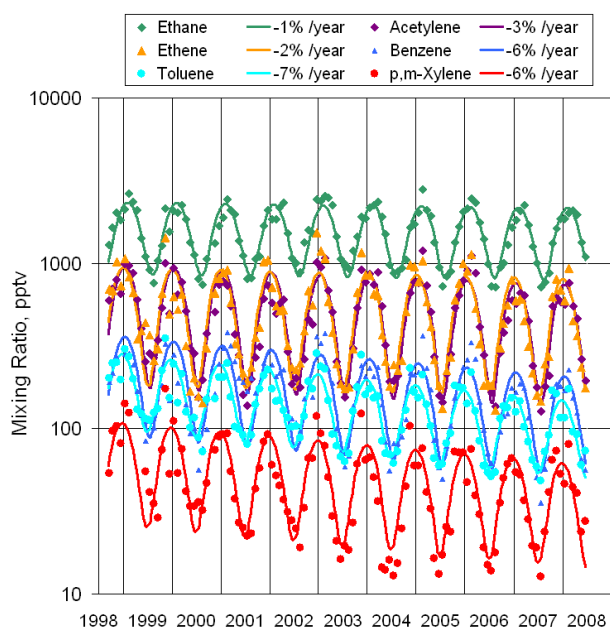
**Figure 1.** Monthly average  $O_3$  mixing ratios from ESRL Global Monitoring Division measurements at Trinidad Head, CA. Results from the Trinidad Head Baseline Observatory surface site (100 m ASL elevation) are compared with the vertical profiles from the weekly ozonesondes. The 1 km contours from the ozonesondes are 200 m averages about the indicated altitude. The error bars indicate the standard deviations about the averages at 2 km altitude.

# Reactive, Anthropogenic Trace Gases at the German GAW Site Hohenpeissenberg: Trends and Variability on Various Time Scales

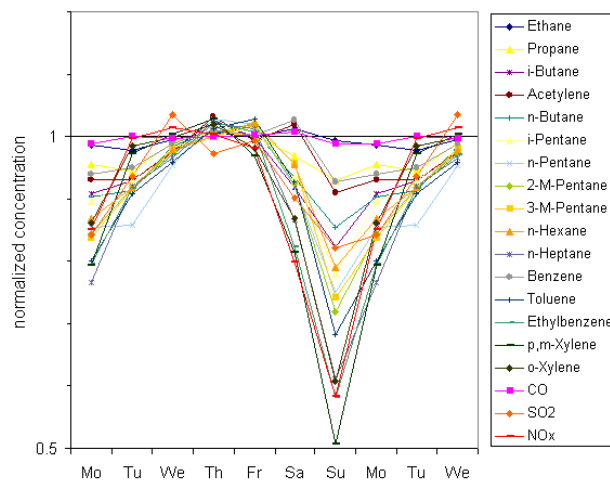
C. Plass-Duelmer and S. Gilge

German Meteorological Service, Albin Schwaiger Weg 10, Hohenpeissenberg, Bavaria 82383, Germany;  
+49-8805-956140, E-mail: christian.plass-duelmer@dwd.de

Atmospheric trace gases show variability on daily, weekly, seasonal and longer time scales due to natural and anthropogenic factors. At Hohenpeissenberg, a global station of the GAW program situated in rural southern Germany, a broad range of different atmospheric trace gases, e.g. VOC, CO, NO, NO<sub>2</sub>, SO<sub>2</sub>, O<sub>3</sub>, OH, has been measured continuously since the mid or end 1990s. Thus, time series of 10 or more years are available now (Figure 1). This enables us to describe the variability and trends and start to analyse the factors of impact. Weekday – weekend comparisons allow a direct estimation of relative changes in anthropogenic emissions (Figure 2). Such differences are significant and increase with shorter life-times of the respective compounds, e.g. xylene concentrations on Sundays are factor 2 lower than during working days. Winter-summer ratios of directly-emitted, anthropogenic compounds generally depend on a combination of changing sources, sinks and transport. Observed winter-summer ratios are mostly between 2 and 6 which are smaller than the summer-winter ratios of OH – radicals of about 8. Trends of the anthropogenic trace gases indicate declining concentrations for most VOC and CO. For NO<sub>x</sub>, however, concentrations did not decline significantly which is in contrast to current emission inventories.



**Figure 1.** Time series of selected NMHC and trends obtained from a sine-fit to the monthly mean mixing ratios.



**Figure 2.** Weekly variation of anthropogenic trace gases at Hohenpeissenberg (daily averages of all data).



## Uptake of Ozone-Depleting Halogenated Gases to the Snow-Covered Surface at Niwot Ridge, CO

D. Helmig<sup>1</sup>, E. Apel<sup>2</sup>, D. Blake<sup>3</sup>, L. Ganzeveld<sup>4</sup>, B.L. Lefer<sup>5</sup>, S. Meinardi<sup>3</sup> and A.L. Swanson<sup>3,6</sup>

<sup>1</sup>Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO 80309; 303-492-2509, E-mail: detlev.helmig@colorado.edu

<sup>2</sup>National Center for Atmospheric Research, Boulder, CO 80307

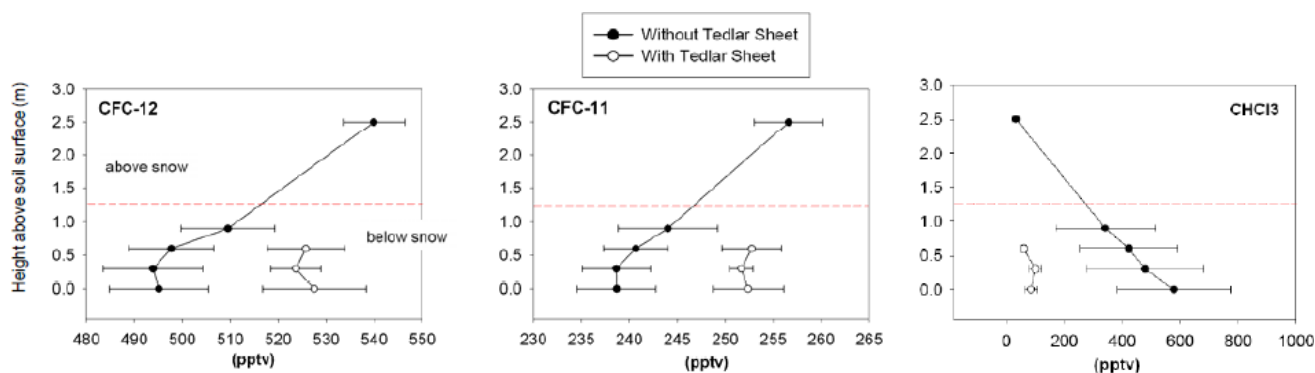
<sup>3</sup>Department of Earth System Science, University of California, Irvine, CA 92697

<sup>4</sup>Department of Environmental Sciences, Wageningen University and Research Center, Wageningen, Netherlands

<sup>5</sup>Earth and Atmospheric Sciences Department, University of Houston, Houston, TX 77204

<sup>6</sup>Department of Chemistry, Northrop Grumman Space Technology, Redondo Beach, CA 90278

Whole air samples were drawn from four heights within the deep winter snowpack at Niwot Ridge, Colorado, during a one-week experiment in March, 2005, and subsequently analyzed by gas chromatography. Two adjacent plots with similar snow cover were sampled, one over natural, vegetated soil, and a second one where the ground was covered with a Tedlar/Teflon film isolating the snowpack from the soil. Samples were also collected from an ambient air inlet above the snow surface. This comparison allowed for studying chemical and physical effects occurring inside the snowpack itself versus effects of soil processes on concentrations and fluxes within and through the snowpack. Here, we focus on findings for a series of halogenated compounds which are of interest for the stratospheric halogen burden and its ozone-depleting potential, i.e. CFC-11, CFC-12, CFC-113, HCFC-22, HCFC-141b, HCFC-142b, methylchloride, tetrachloromethane, methylchloroform, 1,2-dichloroethane, methylbromide, dibromomethane, and bromoform. All of these species were found at lower, i.e. depleted concentrations in the snow, indicating that the snow and/or soil constitute a sink for these gases. A series of other species, including chloroform and dichlorobromomethane, displayed contrasting, i.e. higher concentrations inside the snow, indicating a formation of these gases and release into the atmosphere from this snow-covered environment. Microbial activities below this deep, winter snowpack were determined to be the driving mechanism behind these gas sources and sinks. A snowpack gas diffusion model was applied to develop preliminary gas flux estimates at the snow-atmosphere interface. These flux results were then incorporated into a simple box model to assess the potential contribution of the sink strength of the determined snowpack uptake rates to budgets and atmospheric lifetime estimates of these halogenated gases.



**Figure 1.** Concentration profiles of CFC-12, CFC-11, and CHCl<sub>3</sub> in air samples withdrawn from inlets above and within the snow. The red, staggered line depicts the top of the snowpack surface, which was at 1.3 m above ground. Data are mean values from ~ 3-5 samples collected from each inlet, with horizontal error bars indicating the variability (standard deviation) of each subset of data.

## Springtime Tropospheric Ozone in the Arctic from Surface and Ozoneprobe Observations

S.J. Oltmans<sup>1</sup>, B.J. Johnson<sup>1</sup>, D.W. Tarasick<sup>2</sup>, A.M. Thompson<sup>3</sup> and J.M. Harris<sup>4</sup>

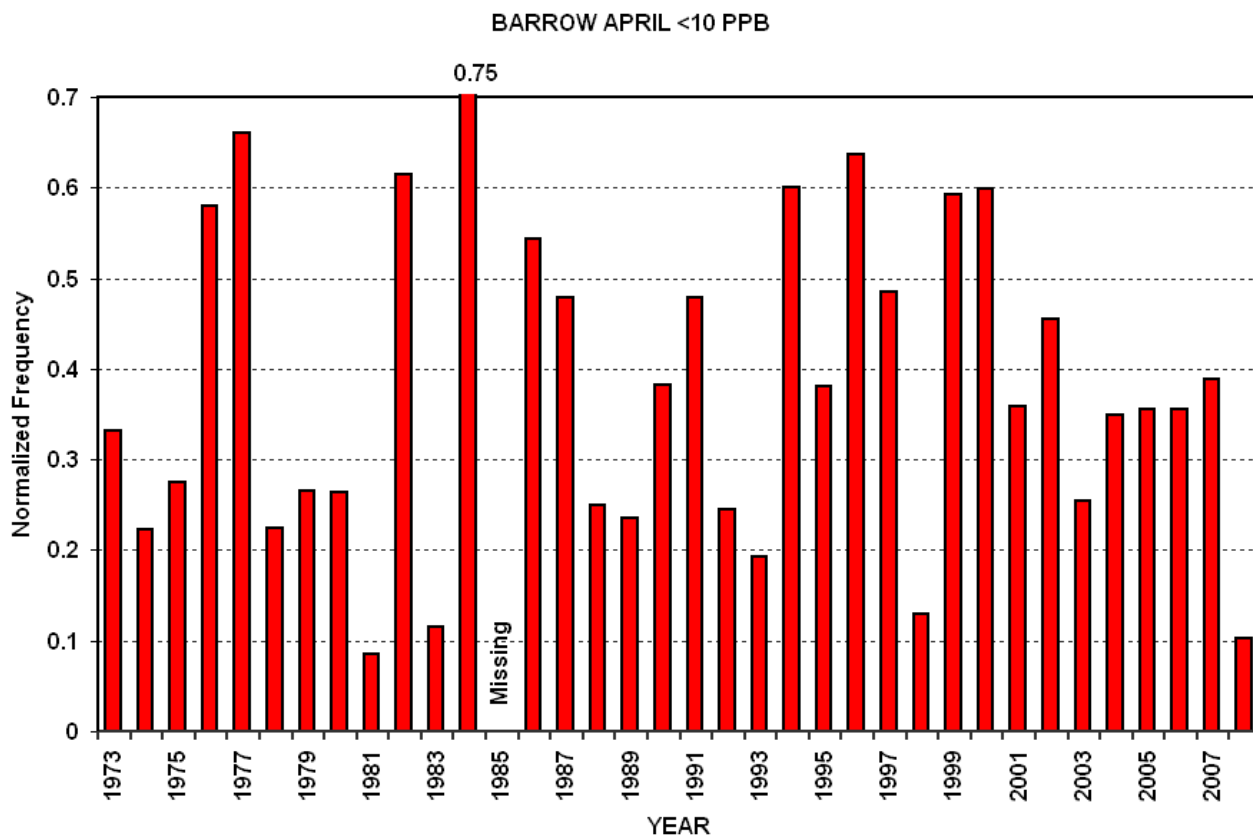
<sup>1</sup>NOAA Earth System Research Laboratory, 325 Broadway, Boulder, CO 80305; 303-497-6676, E-mail: Samuel.J.Oltmans@noaa.gov

<sup>2</sup>Environment Canada, Toronto, Ontario M3H 5T4, Canada

<sup>3</sup>Department of Meteorology, Penn State University, University Park, PA 16802

<sup>4</sup>Science and Technology Corporation, Boulder, CO 80302

During 2008 a number of campaigns focused on Arctic atmospheric composition and the processes that control it. In conjunction with the Arctic Research of the Composition of the Troposphere from Aircraft and Satellite (ARCTAS) project a network of ozone profiling sites carried out near-daily observations during April 2008 and June-July 2008 using balloon-borne ozonesondes as part of the Arctic Intensive Ozonesonde Network Study (ARCIONS). Many of these intensive measurements were done at locations with multi-year ozonesonde observations providing an opportunity for comparison with the 2008 measurements. A notable difference in the spring of 2008 from the longer term observations was the paucity of boundary layer ozone depletion events at the Arctic Ocean coastal locations (Barrow, Resolute, Eureka). At Barrow, Alaska the 35-year record of surface ozone measurements showed that 2008 had the second-lowest occurrence of these events both for the month of April and the spring season (March-April-May) as a whole. The possible meteorological conditions responsible for this year-to-year variability are investigated.



**Figure 1.** Number of hours with ozone  $\leq 10$  ppbv normalized to the number of hourly observations during the month of April for the period 1973-2008.

## Increasing Mid-Tropospheric Ozone Above Western North America During Springtime

O. Cooper<sup>1</sup>, D.D. Parrish<sup>2</sup>, A. Stohl<sup>3</sup>, M. Trainer<sup>2</sup>, P. Nedelec<sup>4</sup>, V. Thouret<sup>2</sup>, J.P. Cammas<sup>1</sup>, S.J. Oltmans<sup>2</sup>, B.J. Johnson<sup>2</sup>, D. Tarasick<sup>5</sup>, T. LeBlanc<sup>6</sup>, I.S. McDermid<sup>6</sup>, D. Jaffe<sup>7</sup>, R. Gao<sup>2</sup>, J. Stith<sup>8</sup>, T. Ryerson<sup>2</sup>, K. Aikin<sup>1</sup> and T. Campos<sup>8</sup>

<sup>1</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309; 303-497-3599, E-mail: owen.r.cooper@noaa.gov

<sup>2</sup>NOAA Earth System Research Laboratory, Boulder, CO 80305

<sup>3</sup>Norwegian Institute for Air Research, Kjeller N-2-27, Norway

<sup>4</sup>Laboratoire d'Aerologie, CNRS – OMP, Toulouse 31400, France

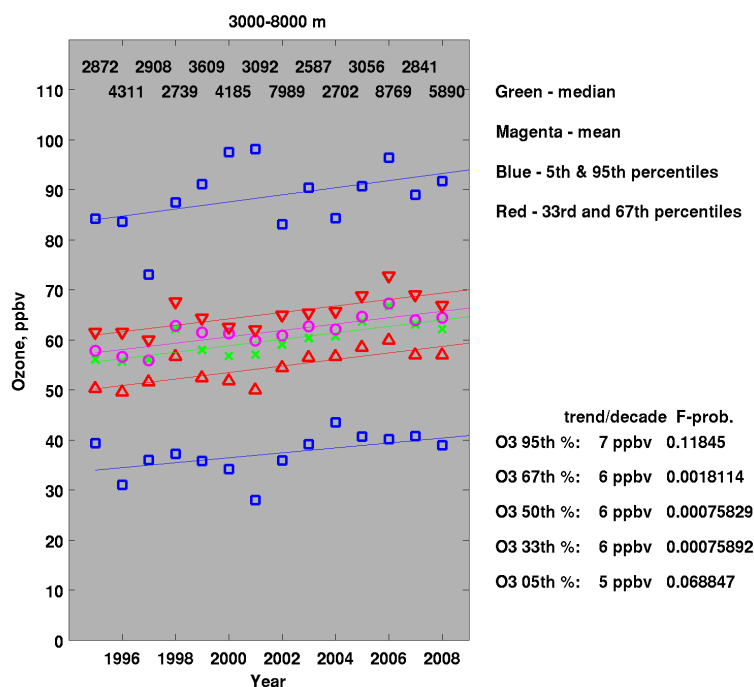
<sup>5</sup>MSC/Environment Canada, Downsview, Ontario M3H5T4, Canada

<sup>6</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

<sup>7</sup>University of Washington - Bothell, Bothell, WA 98011

<sup>8</sup>National Center for Atmospheric Research, Boulder, CO 80305

The interannual variability of mid-tropospheric ozone above western North America has been investigated from *in situ* measurements collected during springtime, 1995-2008. Data were compiled from all available ozonesondes, a ground-based ozone lidar, MOZAIC commercial aircraft profiles, and research aircraft profiles from a variety of field campaigns. For consistency, all profiles were averaged to a regular 20km x 20km x 200m grid, resulting in a 14-year total of 57,500 ozone data points between 3-8 km. Using all available data in the 3-8 km altitude range, a least squares line fit through the median ozone values for each year yields an ozone increase of 6 ppbv/decade, significant at the 99% confidence interval. To examine the impact of the interannual variability of transport pathways, 15-day FLEXPART retrorplumes were calculated for every measurement (a total of 2.3 billion trajectory particles were used in this analysis). The transport history of each measurement, as described by the retrorplumes, was used to remove all data points with a significant influence from the stratosphere or North American surface emissions regions. The increase of ozone associated with background mid-tropospheric air entering western North America is 7 ppbv/decade, significant at the 99% confidence interval. The primary transport pathway of these air masses stretches from east Asia to North America in the 20-40 degree latitude band. On-going analysis of the retrorplumes is aimed at determining if the ozone increase is associated with a broad hemispheric ozone increase or transport from east Asia.



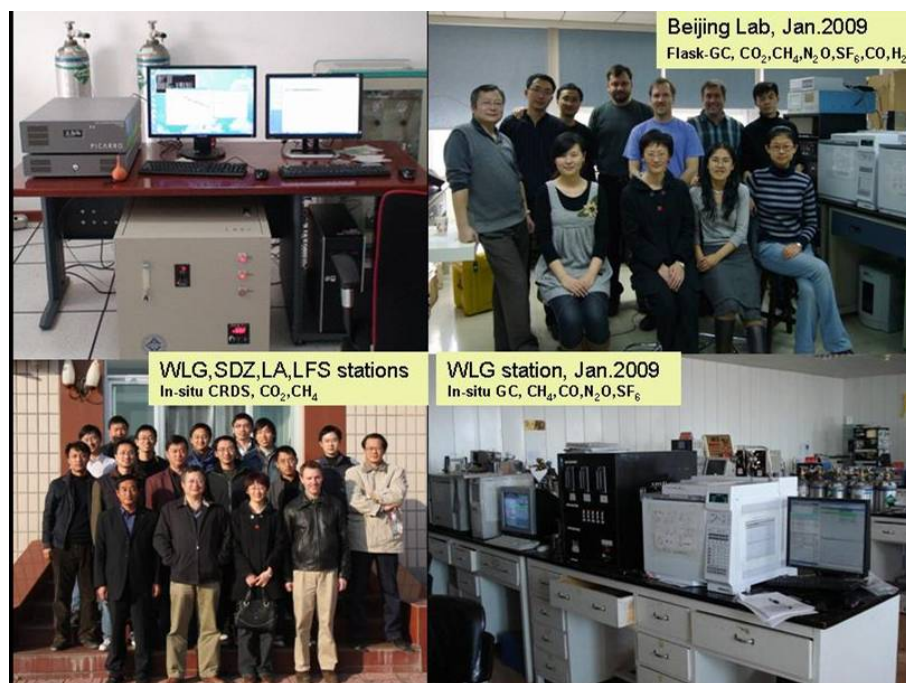
**Figure 1.** Mid-tropospheric (3000-8000 m) ozone above western North America from all available ozonesondes, lidar stations and aircraft measurements during April-May, 1995-2008. Shown are the means (circles), medians (x), 33rd and 67th percentiles (triangles), and 5th and 95th percentiles (squares) for each year with linear regression lines. The ozone increase per decade is shown to the right, with the linear regression significant at the 99% confidence level for the 33rd, 50th and 67th percentiles.

## Updated Outcomes for Greenhouse Gases from China GAW Stations and Near Future Implementation

L. Zhou, L.X. Liu, S.X. Fang, F. Zhang, B. Yao, M. Wen, L. Xu, S. Gu, K.P. Zang and X.C. Zhang

Chinese Academy of Meteorological Sciences (CAMS), China Meteorological Administration (CMA), 46 Zhongguancun Nandajie, Beijing 100081, China; 86-10-58995279, E-mail: zhoulx@cams.cma.gov.cn

Updated outcomes for weekly paired flask samples and *in-situ* measurement program from China GAW stations were presented. Near future monitoring implementation and proposed transfer of the 'Carbon Tracker' model technology and possible vertical profiling of greenhouse gases in background regions of China were introduced. In order to establish a unified Chinese atmospheric greenhouse gases and related tracers observing system, the CMA is keen to work with relevant institutions through further and intensive cooperation especially under the GAW framework. The observing system will be very well calibrated relative to the international WMO standard scale, which is necessary for making proper and full use of the data. The high quality data from background regions of China is essential for integrated database and for modelers to improve our understanding of the carbon cycle and predict how the atmosphere and climate will evolve in the future as a result of human activities.



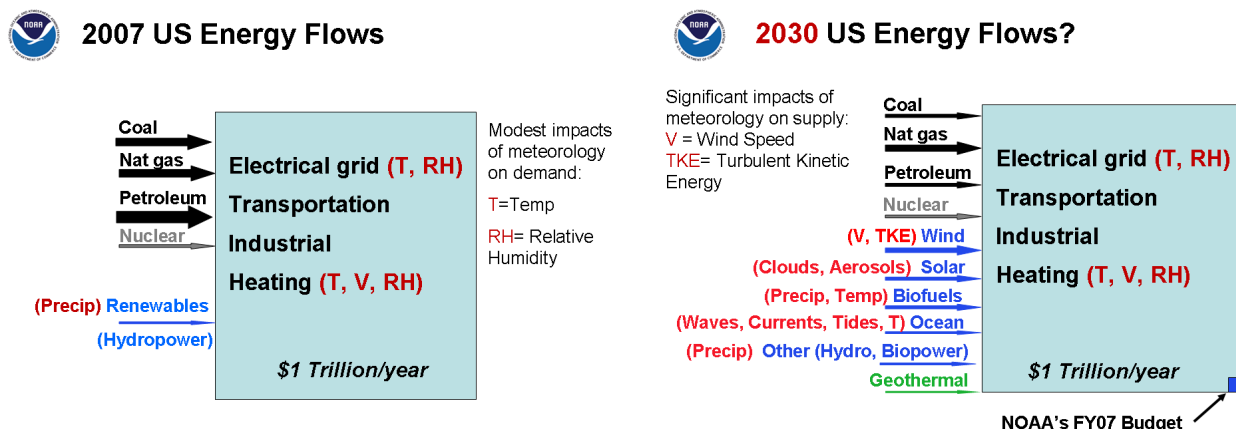
**Figure 1.** Newly established *in-situ* monitoring system at the China GAW stations Waliguan (WLG, 36.29°N, 100.90°E, 3816m asl), Shangdianzi (SDZ, 40.39°N, 117.07°E, 293.9m asl), Lin'an (LA, 30.3°N, 119.73°E, 138m asl), Longfengshan (LSF, 44.73°N, 127.6°E, 310m asl) and Lab analysis/calibration system in Beijing. People showed in the pictures are some of the contributors.

## NOAA's Potential to Support Renewable Energy

M. Marquis

NOAA Earth System Research Laboratory, 325 Broadway, Boulder, CO 80305; 303-497-4487, E-mail: Melinda.Marquis@noaa.gov

The intersection of energy independence, national security, climate, and the economy poses a daunting challenge to the United States and the world. The long-term solutions must include the development of carbon-free renewable energy (RE) sources that are sustainable and economically viable. The current U.S. energy system obtains most of its energy from coal, natural gas, oil, and nuclear plants, with a small contribution from renewable sources (mostly hydropower). Within the next few decades, the U.S. energy system is anticipated to change dramatically. Fossil fuels will have decreased in importance, either through the implementation of climate-oriented policies, or simply because the rate at which we can extract fossil fuels will have decreased, while extraction costs will have risen commensurately. The striking difference between today's U.S. energy system and that for ~2030 is the much greater dependence on renewable energy (RE) production, and the dependence of this production on processes in the atmosphere and ocean. The development of large numbers of wind and solar energy farms depends on a better understanding of the spatial and temporal distribution of wind and solar resources. The integration of wind and solar energy into the electric grid, and demands for transmission and storage, will require very accurate wind and cloud forecasts. On longer time scales, inter-annual and decadal climate variability and change may affect each of these renewable resources. Further, research is needed to determine the inadvertent effect of removing large amounts of atmospheric energy on the environment, weather and climate of varying temporal and spatial scales. Building an efficient and stable national energy supply system in which RE sources contribute significantly will require better meteorological observations, forecasts, analysis tools, and understanding of climate-related issues that are optimized for the renewable energy industry. NOAA's historical responsibility for and expertise in deploying national observing networks, predicting weather and improving forecast models, and understanding and predicting climate, "to meet our nation's economic, social, and environmental needs" is at the nexus of the energy-climate-economy challenge. During the past two years, intensified collaboration with other government agencies, university scientists, and the renewable energy industry, NOAA has identified key steps it can take to support the accelerated development of RE, especially wind and solar energy, in the United States. By hastening the deployment of RE within the United States, NOAA will advance the nation's energy security and independence, boost the economy by the creation of many good jobs that cannot be exported, and reduce emissions of carbon dioxide.



**Figure 1.** The current U.S. energy system relies primarily on fossil fuel energy sources, and has only a negligible dependence of meteorology on supplying energy.

**Figure 2.** The U.S. energy system in a few decades (~2030) is expected to incorporate large amounts of renewable energy sources, which are heavily dependent on meteorology.



## Comparison of Model Predictions of Aerosol Radiative Properties with Long-Term Measurements

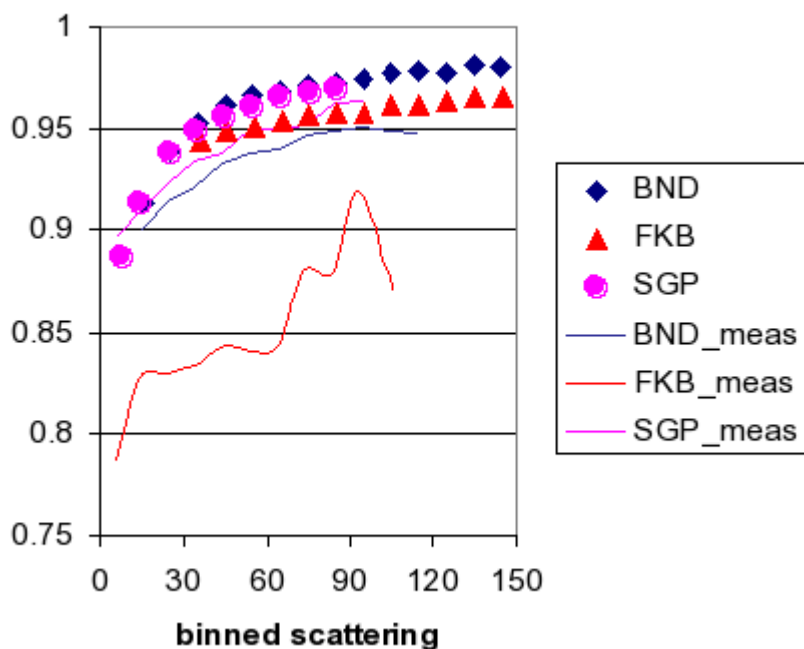
J.A. Ogren<sup>1</sup>, P. Ginoux<sup>2</sup>, E.J. Andrews<sup>3</sup>, P. Sheridan<sup>1</sup> and A. Jefferson<sup>3</sup>

<sup>1</sup>NOAA Earth System Research Laboratory, 325 Broadway, Boulder, CO 80305; 303-497-6210, E-mail: John.A.Ogren@noaa.gov

<sup>2</sup>NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ 08540

<sup>3</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309

Long-term measurements of aerosol radiative properties at a wide range of locations reveal systematic dependencies on aerosol loadings. Aerosols in the cleanest air at any given location tend to be more highly absorbing and more effective at scattering radiation back to space, i.e., they have the lowest single-scattering albedos and the highest hemispheric backscattering fractions. One hypothesis for this behavior is that the cleanest air is a result of scavenging by clouds followed by removal by precipitation. Field studies in a number of locations have shown that the unscavenged particles in clouds indeed have lower single-scattering albedos and higher backscattering fractions than the particles in adjacent, cloud-free air. As a further test of the hypothesis, the statistical behavior of aerosol radiative properties calculated with a global chemical transport model are compared with the long-term observations at sites representative of Arctic, rural continental, marine, and free tropospheric aerosols. The calculations use a version of the GFDL AM2 model, modified to include online aerosols and nudged with the NCEP re-analysis. The results of this measurement-model comparison will be discussed and examined for their implications that the observed systematic dependence of aerosol radiative properties on aerosol amount is caused by cloud scavenging and removal.



**Figure 1.** Comparison of systematic relationship between aerosol single-scattering albedo and aerosol amount (light scattering) at three continental sites, measured (solid lines) vs. model results (symbols). The model reproduces the systematic behavior, but not the value of the single-scattering albedo.

# Trends and Properties of Tropospheric Aerosols That Undergo Long-Range Transport to the North American Arctic

P. Quinn<sup>1</sup>, G.E. Shaw<sup>2</sup>, T.S. Bates<sup>1</sup>, K. Schulz<sup>1</sup>, A. Jefferson<sup>3</sup>, J.A. Ogren<sup>3</sup> and J.F. Burkhart<sup>4</sup>

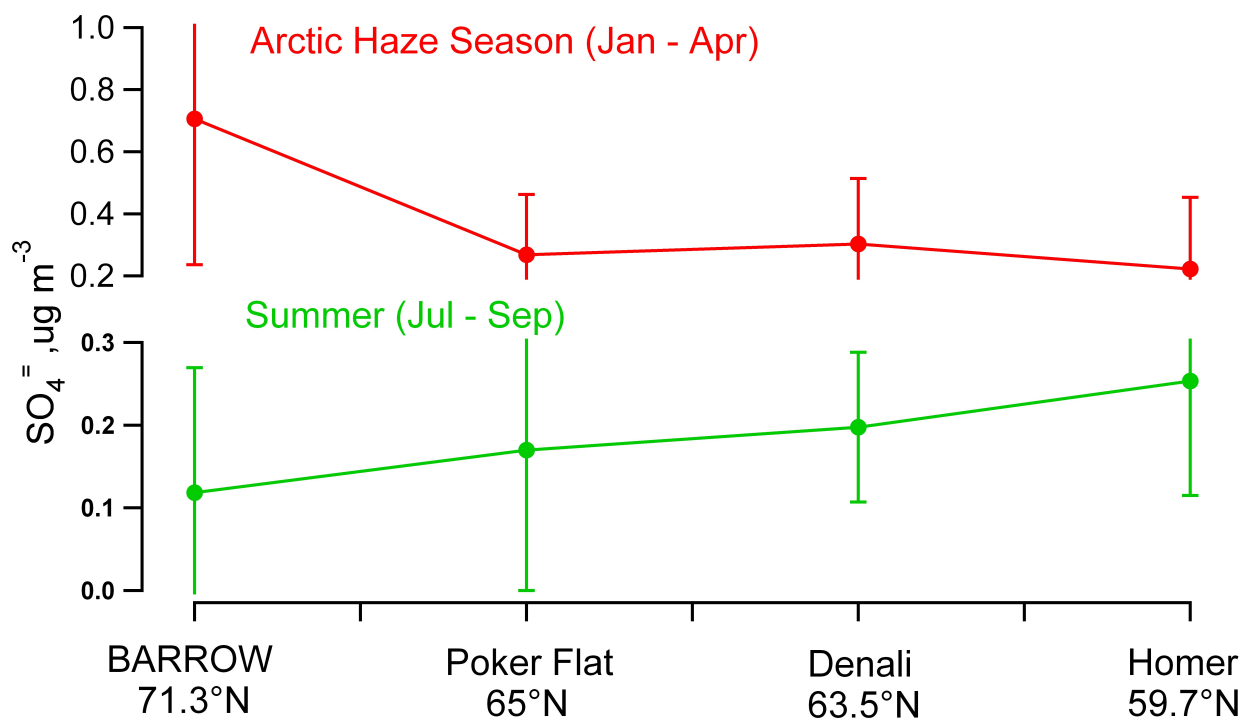
<sup>1</sup>NOAA Pacific Marine Environment Laboratory, 7600 Sand Point Way NE, Seattle, WA 98115; 206-526-6892, E-mail: patricia.k.quinn@noaa.gov

<sup>2</sup>University of Alaska, Fairbanks, AK 99775

<sup>3</sup>NOAA Earth System Research Laboratory, Boulder, CO 80305

<sup>4</sup>Norwegian Institute for Air Research, Kjeller 2027, Norway

Tropospheric aerosol particles undergo long range transport from the mid-latitudes to the Arctic each winter and spring. Once in the Arctic, aerosols may impact regional climate in several ways. Aerosols can affect climate directly by scattering and absorbing incoming solar radiation and indirectly by acting as cloud condensation nuclei and altering cloud properties. In addition, absorbing aerosol that is deposited onto ice and snow can lower the surface albedo and enhance the ice-albedo feedback mechanism. Measurements of aerosol properties relevant to climate forcing (chemical composition, light scattering, and light absorption) have been made by NOAA at Barrow, AK (71.3°N) for over a decade. In addition, for much of this same time period, measurements of aerosol chemical composition have been made at the three more southern Alaskan sites of Poker Flat (65°N), Denali National Park (63.5°N), and Homer (59.7°N). Measurements of sulfate at Barrow reveal a decreasing trend over the past decade of about 1.6% per year for the month of April. This decrease is similar to what has been observed for aerosol light scattering over the same period. Concentrations of sulfate during the Arctic Haze season are highest at Barrow as the Brooks Range hinders transport to the more southerly sites. During the summer, however, concentrations are highest at Homer as a result of biogenic activity. Trends in other species also will be presented and compared for the four sites. In addition, aerosol properties measured at Barrow will be compared to those measured in the European Arctic during the ICEALOT cruise in spring of 2008.



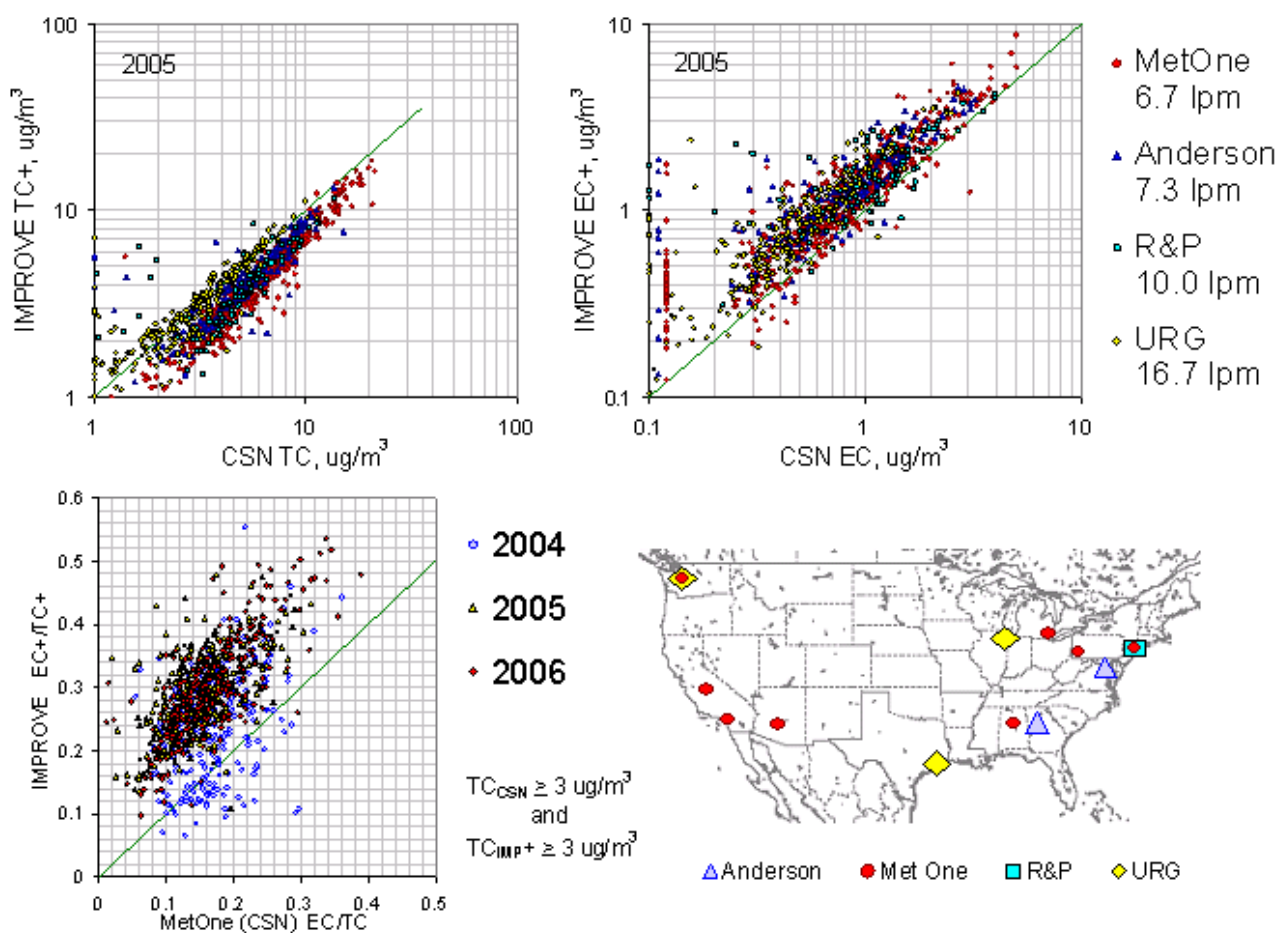
**Figure 1.** Measurements of non-sea salt  $\text{SO}_4$  at four sites in Alaska for the Arctic Haze season (Jan – Apr) and Summer (Jul – Sep).

## Relating OC/EC Data from Two National Monitoring Networks

W.H. White

University of California, Crocker Nuclear Laboratory, Davis, CA 95616; 530-752-1213, E-mail: white@crocker.ucdavis.edu

IMPROVE (Interagency Monitoring of PROtected Visual Environments) is a particle sampling network designed to track regional haze in rural and remote locations. CSN (Chemical Speciation Network) is a particle sampling network designed to support health studies and source apportionment of urban air pollution. Both networks use thermal-optical analyses to determine "elemental" and "organic" carbon in 24-hour samples collected on quartz filters. Differences in their sampler designs, filter handling, analytical protocols and data reduction nevertheless yield significant differences in their reported concentrations. This paper examines the empirical relationships that can be observed in data from several years of collocated monitoring at 12 urban sites, and their implications for integrative data interpretation.



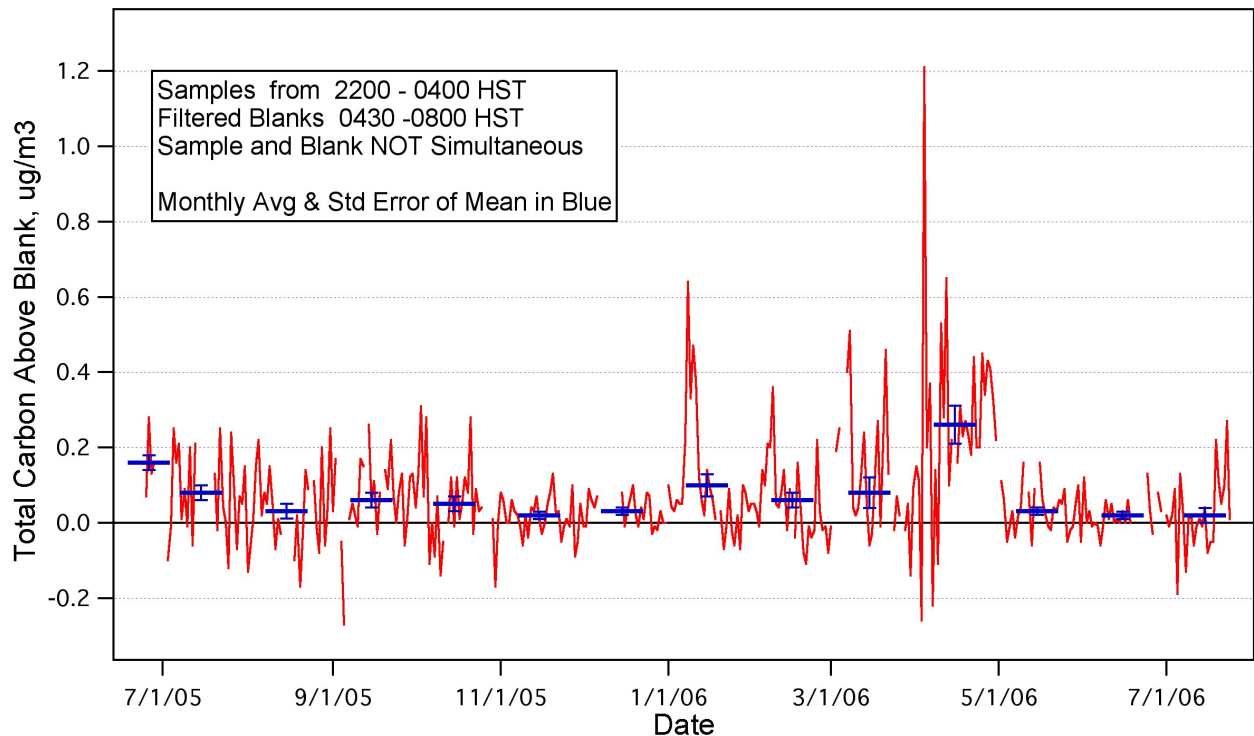
**Figure 1.** Comparisons of IMPROVE and CSN data from collocated monitoring at 12 urban locations (map, bottom right). IMPROVE generally reports more EC than CSN, and less TC than CSN (top); the differences vary with CSN sampler for TC (left), but not for EC (right). The minimum fraction of TC reported as EC by IMPROVE increased in 2005 (bottom left), when aging analytical instruments were replaced. CSN concentrations are reported with no adjustment for sampling artifacts; the "artifact corrections" that are subtracted from reported IMPROVE concentrations were accordingly added back in for these comparisons.

## The Ratio of Total Aerosol Carbon to Sulfate in the Free Troposphere at MLO

B. Huebert, S. Howell and J. Zhuang

University of Hawaii, Department of Oceanography, Honolulu, HI 96720; 808-956-6896, E-mail: huebert@hawaii.edu

There are very few locations from which to make time-series measurements of free tropospheric aerosols, so MLO's location has a unique value. We have measured inorganic aerosol anions and cations and nitric acid vapor nightly at MLO for two decades. We find that Total Carbon (TC) maximizes in the springtime, just as sulfate, nitrate, and calcium do. This is attributed to Asian outflow. However, the TC concentrations at MLO are considerably smaller than those measured in the FT from aircraft during ACE-Asia, suggesting that chemical transport models might not be underestimating OC by as much as Heald et al. (2005) suggest. The ratio of TC to  $\text{SO}_4$  is usually well below one at MLO, in sharp contrast to the higher values just off the Asian coast. Every week or so in the winter we see peaks as large as  $0.5 \mu\text{g TC}/\text{sm}^3$ , but monthly average concentrations (Figure 1) are less than  $0.1 \mu\text{g TC}/\text{sm}^3$  in all months but April (0.25) and August (0.15).



**Figure 1.** Daily (including noise) and monthly-averaged concentrations of Total Carbon at MLO.

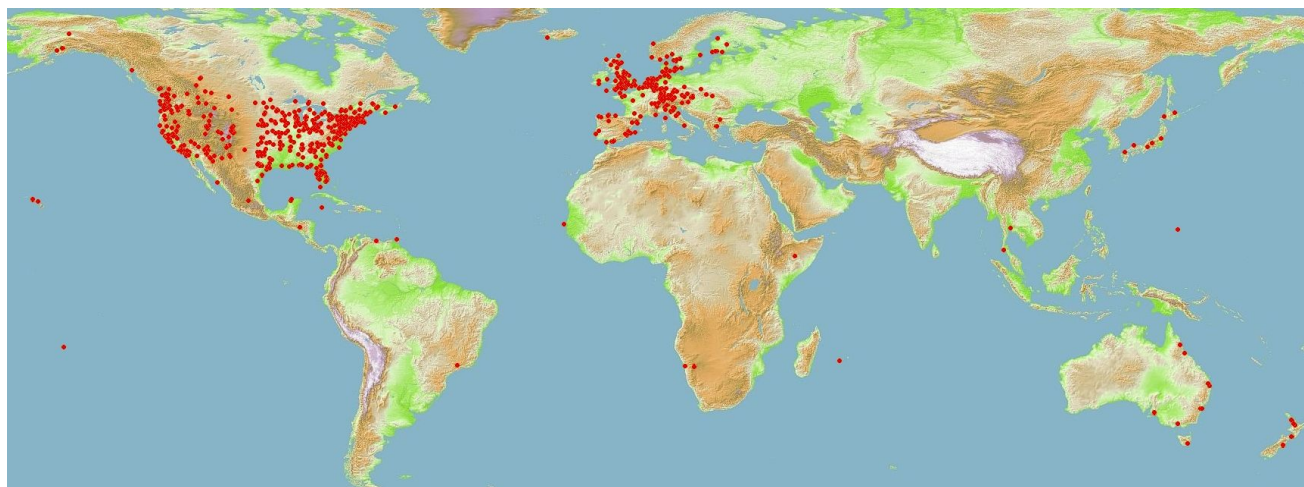
## Solar Radiation Data from Citizen Surface Stations Worldwide

R.B. Chadwick<sup>1</sup> and J.R. Chadwick<sup>2</sup>

<sup>1</sup>NOAA Earth System Research Laboratory, 325 Broadway, Boulder, CO 80305; 303-497-6318, E-mail: Russell.B.Chadwick@noaa.gov

<sup>2</sup>Lockheed Martin, Colorado Springs, CO 80920

Since mid-February, 2009, downwelling solar radiation data from nearly one thousand surface stations, owned and operated by citizens worldwide, have been collected in an online database. The station locations are shown in Figure 1 below. The quality of these data are not well known and have not been studied. This presentation will give the results of a preliminary study on the comparison of some of these data with data from regularly calibrated NOAA Surface Radiation stations at seven sites around the country. More details are given at [http://www.wxqa.com/lum\\_search.htm](http://www.wxqa.com/lum_search.htm)



**Figure 1.** Locations of citizen surface stations contributing solar radiation data.



## Surface Radiation at Globally Remote Sites: From Dimming and Brightening to Warming

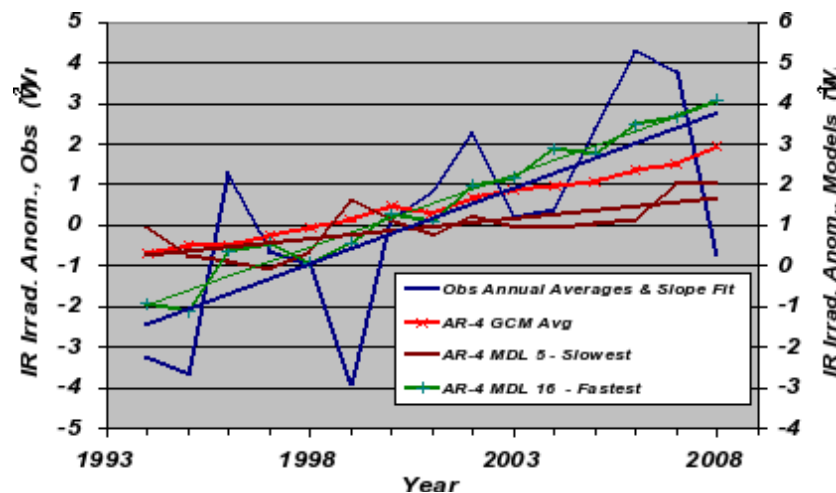
E.G. Dutton<sup>1</sup>, D. Nelson<sup>1</sup>, D. Longenecker<sup>2</sup>, M. Wild<sup>3</sup>, R.S. Stone<sup>2</sup> and J. Wendell<sup>1</sup>

<sup>1</sup>NOAA Earth System Research Laboratory, 325 Broadway, Boulder, CO 80305; 303-497-6660, E-mail: ells.dutton@noaa.gov

<sup>2</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309

<sup>3</sup>Swiss Technical Institute, Zurich, Switzerland

Consistent, long-term, surface radiation observations have been acquired by ESRL from a remote, globally-distributed and climatically-diverse network for more than 30 years for the solar component and 15 years for the thermal IR. The downwelling solar and IR irradiances are major components of the net surface energy budget and are indicative of variations in atmospheric composition as well as the resulting impacts on atmospheric energetics influencing weather and climate. Each of the records, solar and IR from this and other networks have previously indicated interesting variations that warrant further monitoring. The solar irradiance records have indicated larger than anticipated decadal variations, first decreases in the early portion of the record, prior to the mid 1980s, then changing to increases. These features that have been referred to as “Global Dimming then Brightening”, where the term “global” was originally intended to refer to the observed quantity at a particular site. Because a majority of reporting sites around the world appeared to be seeing a similar phenomenon, discussions arose as to whether the term “Global” could be appropriately applied in planetary or worldwide sense. An update on the most recent worldwide surface-base data as it applies to a possible extension of the brightening phase will be provided. The potential role of aerosols and recently suggested aerosol trends in explaining these variations will also be considered. However, taken over the entire period of record not net change in surface solar irradiance can be seen in the longest ESRL data. These variations also have a potential impact on renewable solar energy applications. Regarding the thermal or IR irradiance records, the continued evaluation of the anticipated and previously observed upward trends have now been compared to related results from 22 of the IPCC AR-4 GCM models. The relative agreement between the range of individual models and the observations can be used as one indicator of the model performance given that the comparison is appropriate considering spatial representativeness differences. The globally remote surface IR observations suggest a best-estimate rate of growth that exceeds the consensus of the 22 AR-4 models but that is in close agreement with a small subset of the models displaying the highest IR growth rates over the period of the observations, as shown in Fig. 1.



**Figure 1.** Comparison of IPCC AR4-modeled and ESRL-observed surface downwelling IR radiation, annual average anomalies averaged over 5 globally remote surface sites and corresponding model grid boxes. Right Y-axis shifted to account for different anomaly base periods.

## A New Look at Antarctic Ozone Hole Recovery

D. Hofmann<sup>1</sup>, S. Oltmans<sup>2</sup>, B. Johnson<sup>2</sup> and J. Harris<sup>3</sup>

<sup>1</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309; 303-497-6966, E-mail: David.J.Hofmann@noaa.gov

<sup>2</sup>NOAA Earth System Research Laboratory, Boulder, CO 80305

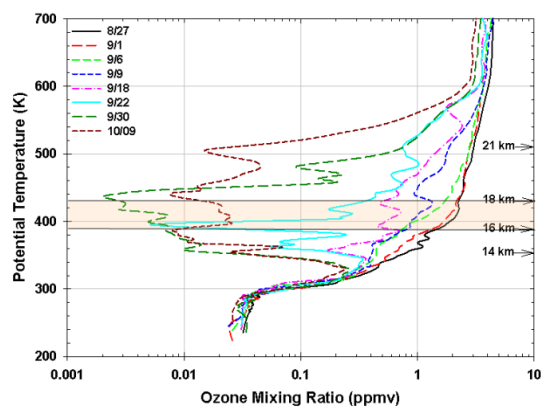
<sup>3</sup>Science and Technology Corporation, Boulder, CO 80305

There have been a number of estimates of when the Antarctic Ozone Hole will recover. These generally include two milestones following the cessation of ozone decline (which occurred about 2000), statistically significant evidence for the beginning of recovery (an ozone increase), and full recovery to 1980 ozone levels. The first attempt (Hofmann et al, 1997), using early estimates for the time evolution of Equivalent Chlorine (chlorine and bromine effects combined), gave approximately 2010 and 2050 for the two milestones. Improved estimates of Effective Equivalent Stratospheric Chlorine (EESC) levels for the future (Newman et al., 2006) indicated that the two recovery milestones for the area of the ozone hole (area within the 220 DU ozone contour) would be considerably later (2024 and 2068).

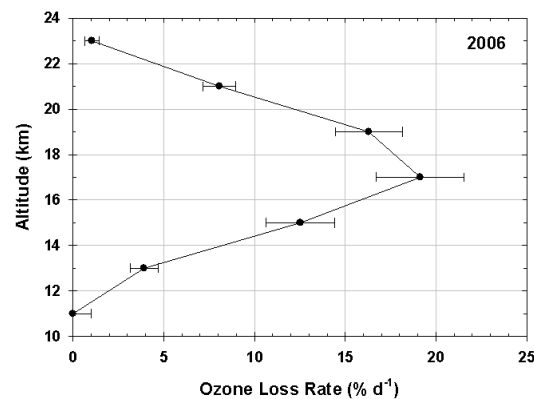
We have reanalyzed the ESRL Global Monitoring Division South Pole ozonesonde data for the 1986-2008 period (see figure 1 for 2006) and found that an exponential ozone loss rate during the September 7 to October 7 period best describes the data in most years. The exponential ozone loss rate (%/day) peaks sharply in the 16-18 km region (see figure 2), slightly below the observed active chlorine (ClO) peak of about 20-22 km. A parametric model using EESC and the stratospheric area of temperatures below the polar stratospheric cloud threshold was used to estimate ozone hole recovery from a South Pole ozone loss rate perspective. The model suggests a threshold EESC value (when ozone loss rate becomes >0) of about 2 ppmv and a saturation EESC value (above which the 16-18 km ozone loss rate does not increase any longer) of about 3.75 ppmv (which occurred about 1993). Two recovery milestones can be defined, when the 16-18 km ozone loss rate comes out of saturation and when full recovery is attained. These are, respectively, 2030-2032 and 2065-2070. It is estimated that the expected stratospheric cooling related to climate change will lengthen the recovery period by one to two years at most.

Hofmann, D.J., S.J. Oltmans, J.M. Harris, B.J. Johnson, and J.A. Lathrop, Ten years of Ozonesonde measurements at the south pole: Implications for recovery of springtime Antarctic ozone, *J. Geophys. Res.*, 102, 8931-8943, 1997.

Newman, P.A., E.R. Nash, S.R. Kawa, S.A. Montzka, and S.M. Schauffler, When will the Antarctic ozone hole recover? *Geophys. Res. Lett.*, 33, L12914, doi:10.1029/2005GL025232, 2006.



**Figure 1.** Ozone mixing ratio profiles at South Pole in 2006 during the formation of the ozone hole. The tan band marks the 16-18 km altitude region where the ozone loss rate is maximum.



**Figure 2.** The ozone loss rate profile during September 7 to October 7 in 2006. The profile peaks at the astonishing rate of 15-20% per day in the 16-18 km region.

## Toward a More Accurate Estimate of Global Stratospheric Aerosol Surface Area Density. Is It Important?

T. Deshler<sup>1</sup>, J.L. Mercer<sup>1</sup>, M. Kovilakam<sup>1</sup>, D.J. Hofmann<sup>2</sup>, J.M. Rosen<sup>1</sup>, S. Solomon<sup>2</sup>, J.F. Lamarque<sup>3</sup>, P.J. Young<sup>4</sup>, R.W. Portmann<sup>2</sup> and J.S. Daniel<sup>2</sup>

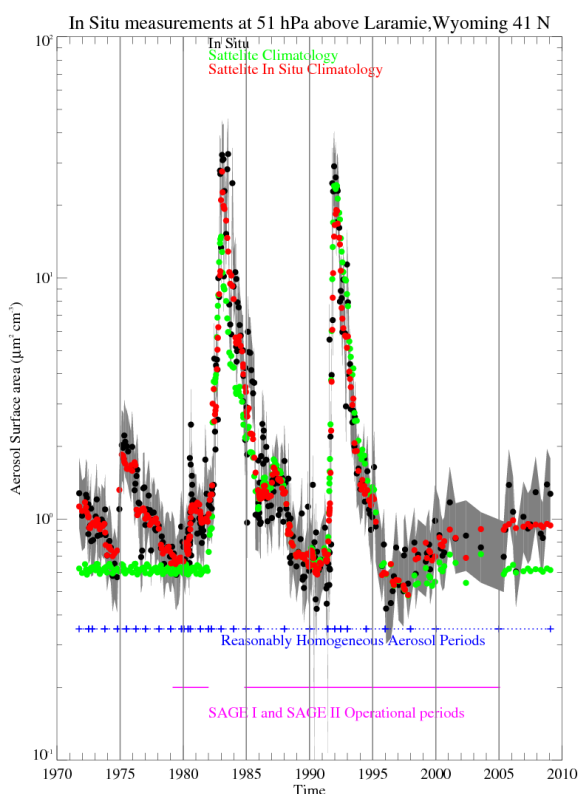
<sup>1</sup>University of Wyoming, Department of Atmospheric Science, 1000 E. Univ. Ave., Laramie, WY 82071; 307-766-2006, E-mail: deshler@uwyo.edu

<sup>2</sup>NOAA Earth System Research Laboratory, Boulder, CO 80305

<sup>3</sup>National Center for Atmospheric Research, Boulder, CO 80303

<sup>4</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309

Stratospheric aerosol, controlled primarily by the transport of tropospheric sulfur bearing molecules into the stratosphere, play important roles in the chemical and radiational balance of the atmosphere. While these aerosol are important radiationally only following major volcanic eruptions, chemically they play an important role in controlling NO<sub>x</sub>, ClO<sub>x</sub>, and HO<sub>x</sub> abundances, and thus O<sub>3</sub>, during periods of both volcanic activity and long volcanic quiescence, such as now. Our current climatology of stratospheric aerosol is based primarily on the SAGE (1979-1982) and SAGE II (1985-2005) satellite records. In addition to these long-term global measurements there are several long-term lidar records (São José dos Campos, Brazil; Mauna Loa, Hawaii; Hampton, Virginia; and Garmisch-Partenkirchen, Germany), and *in situ* size distribution measurements from a number of sites, but primarily from Laramie, Wyoming.



**Figure 1.** Stratospheric aerosol surface area densities from *in situ* measurements above Laramie, from the current surface area density climatology based on SAGE measurements (green), and from the SAGE climatology modified by comparison with the *in situ* measurements. The SAGE and SAGE II operational periods are shown as well as the time periods used to subdivide the record (in blue).

The *in situ* and SAGE II records of aerosol surface area density (SAD) compare favorably during periods of moderate to high aerosol loading, but diverge during periods of stratospheric background, *in situ* (SAD)  $\sim 2 \times$  SAGE (SAD). In addition the *in situ* record precedes and antecedes the SAGE record. The present SAD climatology in use in the modeling community is based on the SAGE records with simple extrapolations applied prior to 1979 and post 2005. The *in situ* record extends from 1971 to 2009. Here the *in situ* record is compared to the SAD climatology above Laramie to form a temporally dependent “corrected” SAD profile. This correction, adjusted to account for transport differences between the northern and southern hemisphere (primarily important for Fuego in 1974), is then applied to produce a “corrected” global SAD climatology from 1971-2009. The corrections become important for the extrapolated periods and the periods of volcanic quiescence in the present climatology. Experimental runs of the community atmosphere model, with the chemical package, using the standard and corrected SAD climatology are in progress. The impact of the corrected SAD climatology on modeled stratospheric ozone over the past 38 years will be compared to model predictions using the standard climatology. During this time chlorine has ranged from pre ozone-hole levels to its recent stratospheric maximum. Results from this comparison will be shown along with the basis for the corrected climatology.

## The GCOS Reference Upper Air Network (GRUAN)

H. Vömel<sup>1</sup>, F.H. Berger<sup>1</sup>, H.J. Diamond<sup>2</sup>, J. Dykema<sup>3</sup>, F.J. Immler<sup>1</sup>, D. Goodrich<sup>4</sup>, W. Murray<sup>4</sup>, T. Peterson<sup>2</sup>, D. Seidel<sup>2</sup>, M. Sommer<sup>1</sup>, D. Sisterson<sup>5</sup>, P. Thorne<sup>6</sup> and J. Wang<sup>7</sup>

<sup>1</sup>Deutscher Wetterdienst, Am Observatorium 12, Tauche / Lindenberg 15848, Germany; +49-33677-60244, E-mail: Holger.Voemel@dwd.de

<sup>2</sup>NOAA National Climatic Data Center, Silver Spring, MD 20901

<sup>3</sup>Harvard University, Cambridge, MA 02138

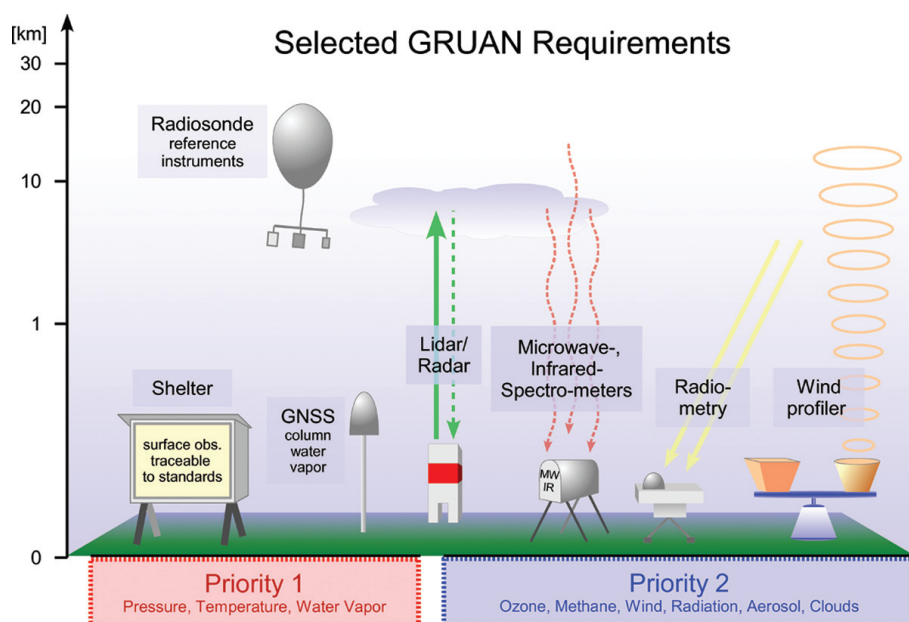
<sup>4</sup>NOAA Climate Program Office, Silver Spring, MD 20901

<sup>5</sup>Argonne National Laboratory, Argonne, IL 54511

<sup>6</sup>Met Office Hadley Centre, Exeter EX1 3PB, United Kingdom

<sup>7</sup>National Center for Atmospheric Research, Boulder, CO 80304

The global upper-air observing network has provided observations for operational weather forecasting for decades, but these observations have shown to be limited to understand upper air climate change. Consequently, the scientific community faces uncertainty on such key issues as the trends of upper air temperature or water vapor. To address these shortcomings, and to ensure that future upper air climate records will be more useful than records to date, the Global Climate Observing System (GCOS) program initiated the GCOS Reference Upper Air Network (GRUAN). This network will provide reference observations of a number of essential climate variables in the troposphere and stratosphere, in particular temperature and water vapor. When fully implemented, GRUAN will be a network of about 30 observatories with a representative sampling of global climatic regions. The network will strongly build on existing networks and utilize existing capabilities, while expanding on upper-air reference observations of key climate variables, such as temperature, water vapor, geopotential height, wind, and a number of additional parameters. GRUAN will strongly focus on vertically resolved measurement uncertainties as a tool for quality quantification. It will use a combination of routine and specialized radiosondes together with complementary remote sensing instrumentation to assure long-term stability, to identify observational weaknesses, and to manage instrumental change, which is one of the most difficult challenges for long-term climate observations. The network will not be globally complete but will serve to constrain and adjust data from more spatially comprehensive global observing systems including satellites and the current radiosonde networks.



**Figure 1.** Proposed instrument suite at a typical GRUAN site.

## Evidence for Recent Stratospheric Circulation Changes from Multiple Measurement Sources

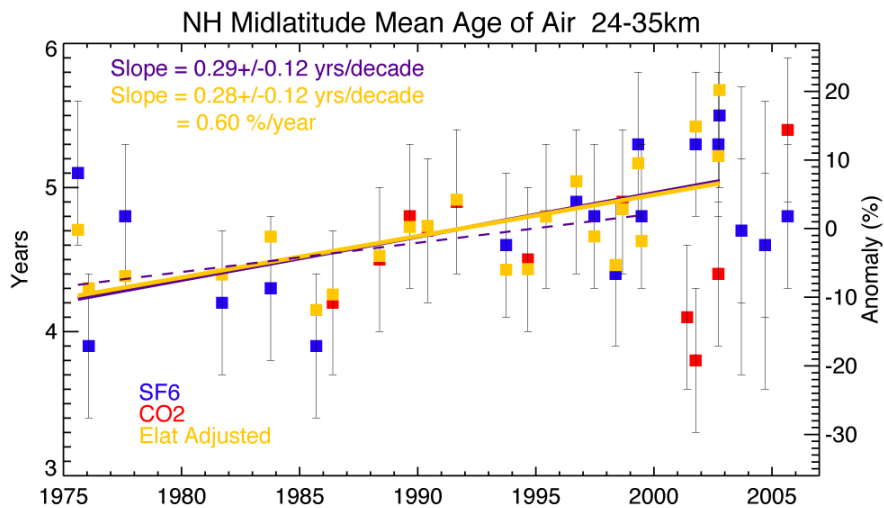
E. Ray<sup>1</sup>, F. Moore<sup>1</sup>, J. Elkins<sup>2</sup>, D. Hurst<sup>1</sup>, K. Rosenlof<sup>1</sup>, A. Engel<sup>3</sup> and S. Oltmans<sup>2</sup>

<sup>1</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309; 303-497-7628, E-mail: eric.ray@noaa.gov

<sup>2</sup>NOAA Earth System Research Laboratory, Boulder, CO 80305

<sup>3</sup>Institute for Atmosphere and Environment, J.W. Goethe University, Frankfurt 60325, Germany

Measured indicators of stratospheric circulation changes have been difficult to attain due to a lack of sufficient long-term stratospheric measurements. Several such datasets do exist however and each of them, such as stratospheric water vapor mixing ratios measured over Boulder, CO, suggest that changes have occurred in the stratosphere over the last 25 years. We show that the changes seen in the measured or measurement-based indicators of stratospheric circulation, including stratospheric water vapor measurements, a residual circulation calculation and age of air estimates, are consistent with each other. Collectively these datasets help to describe the two main features of recent stratospheric circulation changes: (1) a trend of increasing water vapor mixing ratios and age of air from 1980-2000, and (2) a large, persistent shift during the year 2000 towards increased mass flux in the lower stratosphere, decreased water vapor mixing ratios and decreased age of air. Global climate models have been unable to reproduce either the correct trend or the subsequent large shift in the stratospheric circulation. It is likely that these stratospheric changes are driven by changes in tropospheric wave activity that induces changes in both mean circulation and mixing between the tropics and extratropics. We will include a brief analysis of Eliassen-Palm flux divergence statistics calculated from the NCEP Reanalysis dataset as an indicator of wave driving of the stratosphere to begin to analyze the cause of the changes. We will also look for changes in measured stratospheric tracer-tracer correlations that can only occur due to circulation changes. These observed changes in the stratosphere provide a large constraint on global climate models and it is clearly important to more fully understand their causes.



**Figure 1.** The figure shows mean ages in the 24-35 km altitude range calculated from SF<sub>6</sub> (blue squares) and CO<sub>2</sub> (red squares) measurements taken in various locations in the NH midlatitudes (Engel et al., 2008). Since the equivalent latitudes of the measurements ranged from 28-57°N we adjusted the mean age age values by removing the linear fit of mean age vs. elat to reduce any bias in the trend related to measurement location. The yellow squares in the figure are the equivalent latitude adjusted mean ages. The calculated linear fits from 1975-2002 are very similar and are significantly positive whether using the original or elat adjusted mean ages. The main difference is that the goodness of fit is reduced by over 30% in the fit to the elat adjusted ages indicating that the spread in the data is significantly reduced by the equivalent latitude adjustment.



## UV Products from NOAA-EPA Brewer (NEUBrew) Network

P. Kiedron, P. Disterhoft, K. Lantz, I. Petropavlovskikh and S. Stierle

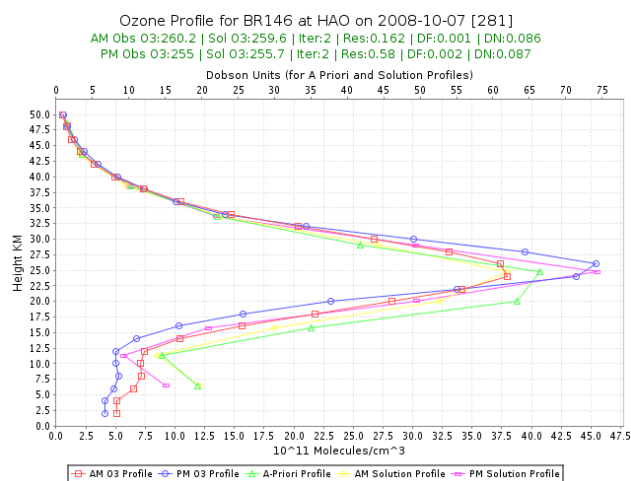
Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309;  
303-497-4937, E-mail: peter.kiedron@noaa.gov

The NEUBrew network is a collaborative monitoring and research effort between NOAA ESRL and EPA's Office of Air Quality, Planning and Standards (OAQPS). The network was established in the last half of 2006 by deploying MKIV Brewer spectroradiometers at six sites throughout the U.S. (University of Houston, TX, Table Mt., Boulder, CO, University of Colorado's Mountain Research Station, Niwot Ridge, CO, Rayleigh, NC, Bondville, IL, and Ft. Peck, MT). Each spectroradiometer was calibrated radiometrically and calibrated for the ozone retrieval. An optimized schedule to obtain the maximal duty cycle was developed. It includes measurements of O<sub>3</sub> and SO<sub>2</sub> columns from direct sun and zenith radiance; dawn and dusk Umkehr measurements, zenith radiance NO<sub>2</sub> measurements and UV global irradiance scans in the 286.5 - 363.0 nm range. Data processing includes extensive automated diagnostic tools. The results in graphical form are available via the web page<sup>1</sup> and the text files via the public ftp site<sup>2</sup>. UV irradiance went through first two levels of quality control: irradiances are radiometrically calibrated with CUCF lamps, corrected for artifacts and corrected for internal stray light. Irradiances are used to calculate erythema and UV index.

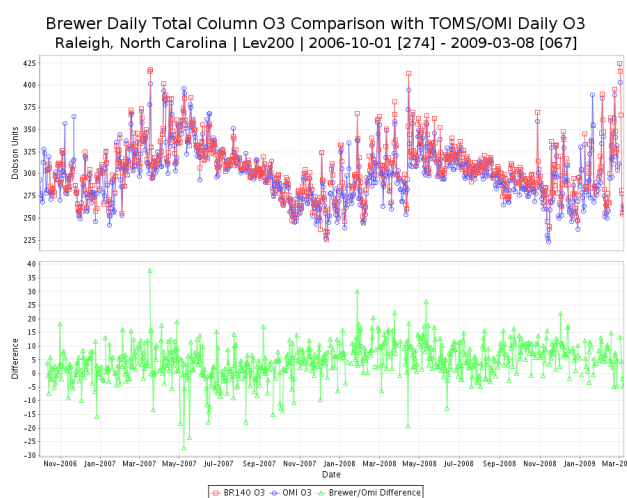
The UV index is compared with the 5-day forecast from the National Climate Prediction Center (NCEP). Umkehr data are processed daily to retrieve up to two (AM and PM) ozone vertical profiles. An additional extrapolation method was implemented to assess inter-annual ozone variability in troposphere. Ozone column level 2 data use a correction of the extraterrestrial constant (ETC) based on daily internal lamp measurements. Results are compared with daily OMI ozone. For some instruments that exhibited throughput drift of solar blind NiSO<sub>4</sub> filter, the correction is significant. Additionally, the ETC is verified against results from Langley plots. Raw data from O<sub>3</sub> and NO<sub>2</sub> measurements will also be used to retrieve aerosol optical depth (AOD) in 310 – 320-nm region and in 430-nm region.

<sup>1</sup> <http://esrl.noaa.gov/gmd/grad/neubrew/>

<sup>2</sup> <ftp://ftp.srrb.noaa.gov/pub/data/neubrew/data/products/>



**Figure 1.** Ozone vertical profile retrieved with Umkehr method.



**Figure 2.** Daily average ozone column level 2 compared with OMI ozone.

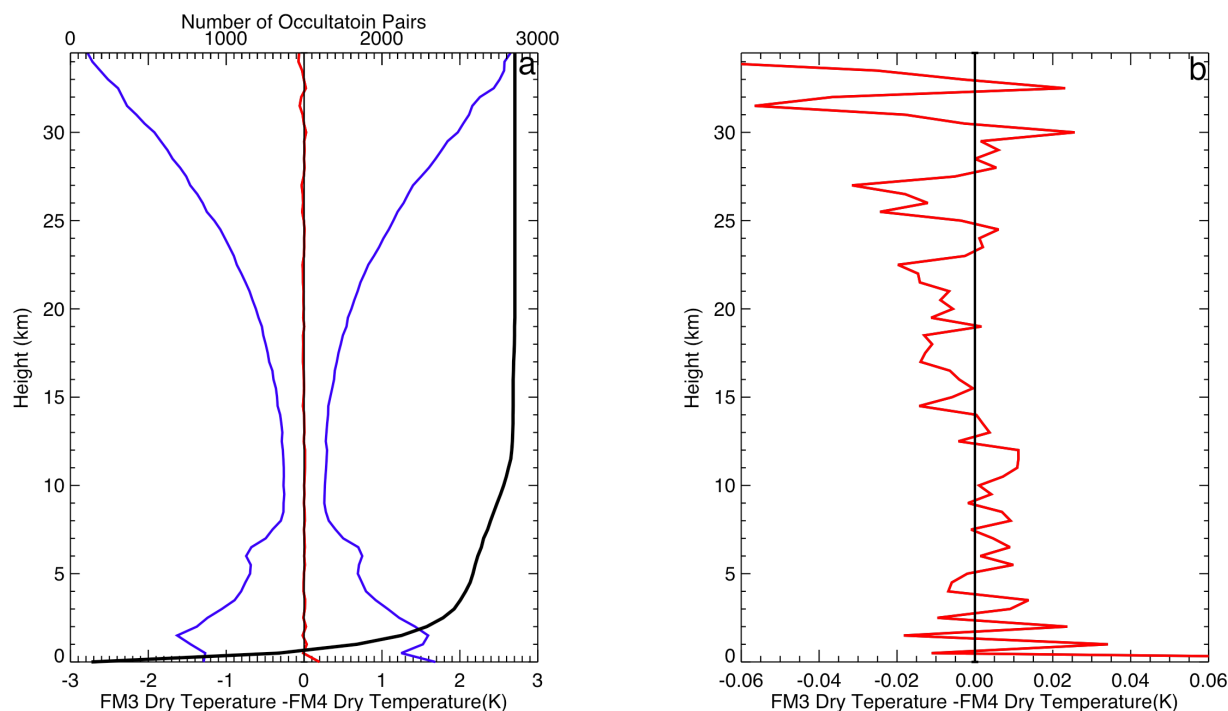
## Applications of COSMIC Radio Occultation for Climate Monitoring

S. Ho<sup>1</sup>, Y.H. Kuo<sup>1</sup>, D. Hunt<sup>1</sup>, C. Rocken<sup>1</sup>, W. Schreiner<sup>1</sup>, S. Sokolovskiy<sup>1</sup>, R.A. Anthes<sup>1</sup> and K.E. Trenberth<sup>2</sup>

<sup>1</sup>University Corporation for Atmospheric Research, COSMIC Program, P.O. Box 3000, Boulder, CO 80307; 303-497-2922, E-mail: spho@ucar.edu

<sup>2</sup>National Center for Atmospheric Research, Boulder, CO 80307

Global Positioning System (GPS) Radio Occultation (RO) is a powerful remote sensing technique to provide global all-weather vertical profiles of refractivity, which is a function of temperature, water vapor and pressure. The six-satellite COSMIC mission was successfully launched in April 2006. After the satellites were deployed to operational orbits, ~1,500-2,000 GPS RO soundings are available over the globe every 24 hours. The early phase of the COSMIC mission, when these six COSMIC receivers were closely located, provided a unique opportunity to test the precision of GPS RO measurements, because the independent RO signals travelled through nearly the same atmospheric paths. Comparisons from two COSMIC receivers show that the ranges of median values of dry temperature difference from surface to 30 km are within 0.05 K, and as small as 0.02 K from 3 km to 25 km. The precision of better than 0.05 K in the mean confirms that RO data are benchmark climate observations, and are ideally suited to monitoring climate variability and trends from the surface to 30 km. Applications of COSMIC RO data for climate monitoring are presented.



**Figure 1.** (a) The median and the median absolute deviation (MAD) of the dry temperature difference between two COSMIC satellites (FM3 and FM4) from 2006, day 111 through 300 where the distance between FM3-FM4 receivers is within 10 km. The red line is median, the blue line is MAD, and the black line is the number of the FM3-FM4 profile pairs used in the comparison at various vertical levels. (b) The median of the dry temperature difference between FM3-FM4 as in (a) but on a much smaller temperature scale in x-axis.

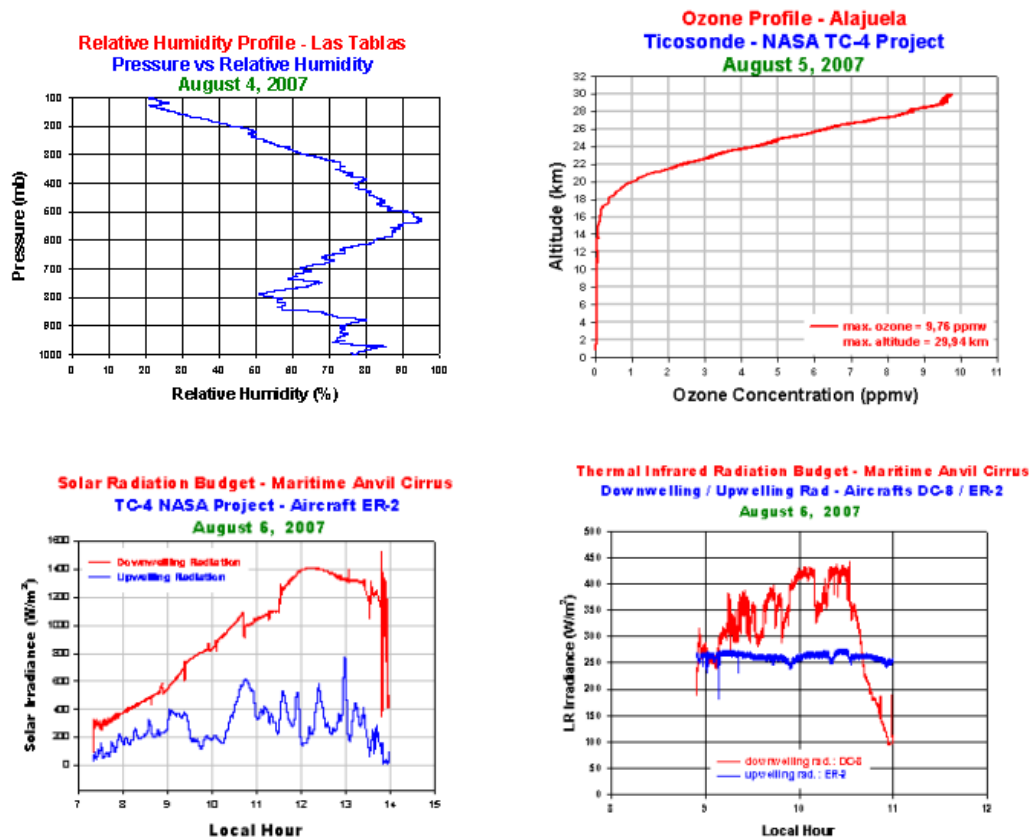
## Behavior of Some TC-4 Atmospheric Parameters Measured by Balloonsondes and NASA Aircraft

A. Pino<sup>1</sup>, S. Guerra<sup>1</sup>, D. Castillo<sup>1</sup>, A. Maturell<sup>1</sup>, J. Espinoza<sup>2</sup>, H. Samudio<sup>1</sup> and L. Jordán<sup>1</sup>

<sup>1</sup>Laboratory of Atmospheric Physics of the University of Panama, Ave. Simon Bolivar, El Cangrejo, Republic of Panama; 011-507-523-5328, E-mail: atmosfer@ancon.up.ac.pa

<sup>2</sup>Panama Canal Authority, Hydrometeorology Department, Republic of Panama

The Laboratory of Atmospheric Physics of the University of Panama collaborated with NASA TC-4 field campaign during July and August, 2007. To study the profiles of some atmospheric parameters, balloonsondes were launched twice daily from San José, Costa Rica and Las Tablas, Panama. One of these parameters is relative humidity whose daily vertical structure is associated with tropical deep convection. Relative humidity behavior through upper troposphere and lower stratosphere is very important in order to assess the contribution of water vapor to climate change, since water vapor is the most powerful greenhouse gas. Relative humidity, temperature and ozone profiles obtained from data collected with sondes launched from Panama and Costa Rica, during TC-4, are analyzed. Relative humidity profiles show inversion layers near 550 mb which are linked with deep convection processes occurred previously. Radiative forcing from maritime anvil cirrus plays an important role in the modulation of climate change, since these clouds have a cooling effect as a consequence of scattering incoming sunlight by cirrus ice crystals. But these clouds also have a warming effect due to the fact that they absorb upwelling thermal infrared radiation emitted from the surface. During TC-4, several coordinated flights of ER-2 (over the cirrus layer) and DC-8 aircraft (below the cirrus layer) were planned. A discussion of the incoming solar radiation budget as well as the thermal infrared radiation budget measured during the coordinated flights occurred on August 6, 2007, will be presented.



**Figure 1.** a) Relative humidity profile (Las Tablas). b) Ozone Profile (Alajuela). c) Solar Radiation Budget (Maritime Anvil Cirrus). d) Thermal infrared radiation budget (Maritime Anvil Cirrus).

## Rapid Photochemical Production of Ozone at High Concentrations in a Rural Site During Winter

R.C. Schnell<sup>1</sup>, S.J. Oltmans<sup>1</sup>, M.S. Endres, J.V. Molenaar<sup>3</sup>, R.R. Neely<sup>4</sup> and A.B. White<sup>1</sup>

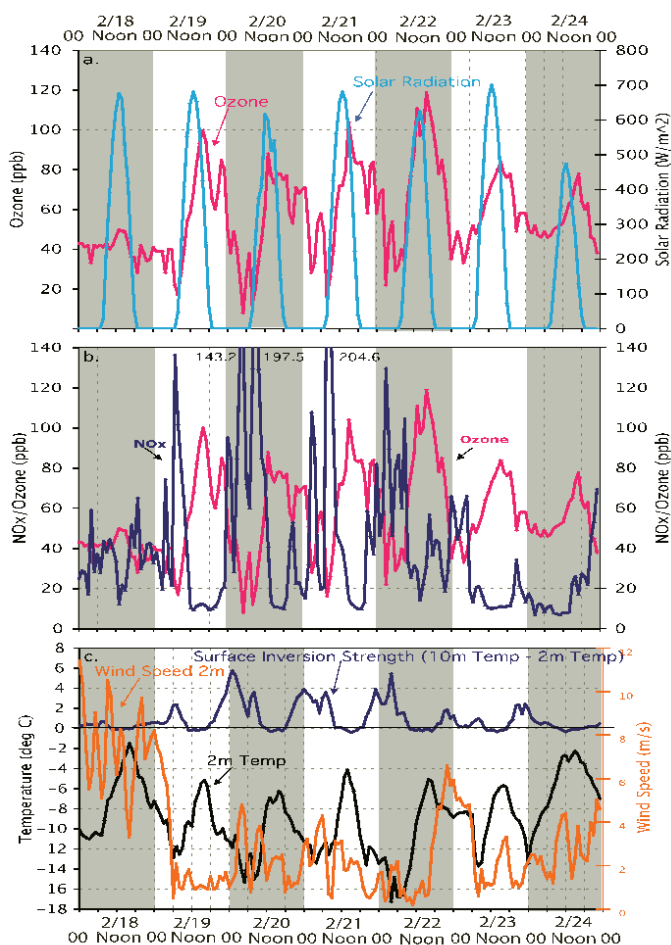
<sup>1</sup>NOAA Earth System Research Laboratory, 325 Broadway, Boulder, CO 80305; 303-497-6733, E-mail: russell.c.schnell@noaa.gov

<sup>2</sup>Wyoming Department of Air Quality, Cheyenne, WY 82002

<sup>3</sup>Air Resource Specialists, Fort Collins, CO 80525

<sup>4</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309

Ozone is an air pollutant that can cause severe respiratory health effects. Photochemical ozone production near the Earth's surface is considered a summertime, urban phenomenon, where hourly average ozone concentrations may exceed 150 ppb compared to background values of ~50 ppb, and wintertime U.S. ozone concentrations are generally 35-50 ppb. We have recently documented rapid, diurnal, wintertime, cold temperature, photochemical ozone production in the rural Upper Green River Basin (UGRB), Wyoming, in the vicinity of the Jonah-Pinedale Anticline (JPA) natural gas field, at air temperatures as low as -17°C. In these events, hourly average ozone concentrations rise from 10-30 ppb at night to >140 ppb shortly after solar noon, under the influence of a stagnant, high pressure system that promotes cold temperatures, low wind speeds and limited cloudiness. Under these conditions, intense, shallow temperature inversions develop in the lowest 100m of the atmosphere, that trap high concentrations of ozone precursors at night. During daytime, photolytic ozone production then leads to rapid daytime photolytic ozone production. We have recently also observed this phenomenon in NE Wyoming near a coal mining area, in a natural gas field in northern New Mexico, and in an urban area (Logan, Utah).



**Figure 1.** Hourly average solar radiation, ozone, NOx and temperature data for the Jonah air quality monitoring site, Feb 18-25, 2008 showing rapid ozone production closely tracking solar radiation with a 1-2 hour time lag and associated NOx, temperatures and winds.